Human Factors Evaluation of Caution and Warning Interface Concepts for Project Constellation Vehicles

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Table of Contents

1. Introduction

1.1. Caution and Warning Systems on Today's Crewed Vehicles

Human-rated spacecraft contain a large number of complex and often interconnected engineering systems. The list includes vehicle propulsion systems, electrical, hydraulic, and mechanical power generation and distribution systems, guidance, navigation, and control (GN&C) systems, data processing systems, environmental control and life support systems, and communications systems. Particularly during the dynamic flight phases of launch, ascent, and entry, these systems must perform to precise operational specifications in harsh environments whose cumulative effects on system functioning are often poorly understood. As a result, systems malfunctions are an ever-present threat to mission success and crew safety.

Systems designers respond to the threat of malfunctions by building in functional redundancies wherever possible. If a system component fails during flight, crewmembers can then exploit these redundancies to restore nominal system operations by, for example, switching to a backup component or a backup operational mode. While that may sound straightforward, the actual process of detecting, identifying, and working systems malfunctions on a vehicle as complex as a spacecraft is quite complicated. To begin with, the onboard sensors generate far too much telemetry to display to the crew at any one time. Therefore, all spacecraft require a Caution and Warning (C&W) system whose primary functions are to *detect* anomalous sensor readings that could indicate the presence of a malfunction and *annunciate* the anomalous situation to the crew. These functions are enabled by fault detection and annunciation (FDA) software that performs continuous limit checking on literally thousands of flight (speed, altitude, attitude, etc), and systems-related (temperatures, pressures, flow rates, voltages, currents, etc) parameters. When a parameter reading goes outside the preset limits, the C&W system alerts the crew with a variety of visual cues and auditory alarms that collectively constitute a C&W event.

Perhaps the most important visual cues are the written fault messages. These messages aid the crew in diagnosing the source of the event (i.e., diagnosing the cause), and also help the crew locate the appropriate checklist of fault isolation and recovery procedures. In NASA's shuttles, these checklists are available only in paper documents or on cue cards. Wherever possible, the C&W fault messages are written to be isomorphic with the titles of the checklists. Once a C&W message is identified as the root cause, the crewmember locates the set of procedures with that message as its title, and starts to follow the procedures.

Unfortunately, C&W events have well-recognized human factors problems that often complicate the process of diagnosing the underlying (root) cause (McCandless, Hilty, & McCann, 2005; McCann, et al., 2006). Fault Detection and Annunciation (FDA) or limit-sensing software processes each sensor's data independently, so the C&W system cannot discriminate a legitimate off-nominal reading from an out-of-limits reading due to a failed sensor, or to a limit that is inappropriate for the current flight phase or configuration. These lead to false alarms. More seriously, due to the complex and often highly interconnected nature of the onboard systems, a failure of one component frequently causes additional abnormal sensor readings and changes in the operational status of subsystems and equipment downstream of the instigating failure. When these forms of failure propagation occur, the result is a cascade of fault messages and other visual indications that distract the crew, impair their situation awareness, and hamper their ability to decipher the event (McCandless, McCann, & Hilty, 2003).

Malfunction identification marks the end of C&W system involvement in the fault management process, and the vehicle provides little more assistance (or hindrance) with the fault management activities that still remain. Crewmembers must manually locate the correct set of procedures, manually navigate through the procedures, and manually perform all systems and vehicle reconfiguration commands via physical switches. These operations are often slow, inefficient, attention-demanding, and error prone. They can have a severe impact on situation awareness during dynamic flight phases, when the crew has to divide their attention between working the malfunction and monitoring the vehicle's critical systems and navigation state (McCann, et al., 2006).

1.2. Off-Nominal Situation Management on Next-Generation Crewed Vehicles

Project Constellation flight vehicles are going to have much less interior volume than the shuttles. This constraint, along with the fact that the Orion Crew Exploration Vehicle (OCEV) is expected to have higher peak g loadings and vibration levels than the shuttles, is forcing most vehicle operations concepts to be designed around electronic crew-vehicle interfaces. With almost no interior room for the physical switch panels that dominate the cockpits of the shuttles and previous crewed spacecraft, for example, virtually all vehicle commanding will take place through soft commanding interfaces. Most nominal and off-nominal procedure checklists will be stored in computer memory, rather than on paper, and crews will locate and navigate through checklists via an electronic procedure viewer. Last but not least, crewmembers' arms will be restrained during dynamic flight phases, necessitating an operations mode in which all crew-vehicle interactions are accomplished through one or more handheld devices usable under high g loads and vibration levels. As these devices represent a form of remote control, virtually all operations with these devices require electronic interfaces.

Nowhere is the influence of these factors more direct than on the operations concept for off-nominal situation management. Earlier, we noted that many of the difficulties associated with today's fault isolation and recovery operations stem from the fact that checklist navigation and vehicle commanding are largely manual activities. In Constellation Project vehicles, the conversion to electronic checklists offers many opportunities to assist the crew with checklist access and navigation. For example, the electronic checklists in today's airline cockpits offer many examples of display-based navigation aiding. Their electronic procedure viewers indicate the next procedure to be completed by highlighting the currently active line with an outline box, move the box to the next line when the procedure in the current line is completed, and automatically skip lines that belong to inapplicable branches of conditionals.

The potential benefits of electronic interfaces for off-nominal situation management extend well beyond procedure navigation. The transition from manual to electronic interfaces for vehicle commanding opens up several opportunities to support a more integrated concept of off-nominal operations. One example is increased coordination between checklist navigation and vehicle commanding. In one of the conditions we explore in this human factors evaluation, systems commanding takes place via switch icons depicted on virtual switch panels. When the current step (current line) in a procedures checklist calls for changing the mode of a particular switch (e.g., taking a switch from "off" to "on") on a virtual switch panel, a bright green rectangular outline appears around the relevant switch icon, visually cuing the crewmember to the relevant element on the panel. And since the C&W interfaces are already largely electronic, further opportunities exist to integrate the fault diagnostic (C&W) interfaces with the subsequent isolation and recovery interfaces. The display formats we investigate here incorporate C&W visual alarms and written fault messages into an integrated fault management display format that incorporates system summary displays, vehicle commanding displays, and an electronic procedures viewer.

We will have more to say about the design of these interfaces shortly. For now, suffice to say that the greater use of electronic interfaces on Project Constellation flight vehicles offers abundant opportunities to enhance crewmembers abilities to work malfunctions more autonomously than is possible today.

1.3. Advanced Caution and Warning Systems on Next-Generation Vehicles

Previous work (McCann, et al, 2006) in part-task simulations of shuttle ascents has confirmed that fault isolation and recovery operations improve dramatically when handled through electronic interfaces. By themselves, however, electronic procedure viewers and soft commanding interfaces don't directly address the problems associated with processing and understanding C&W events. These problems were judged serious enough by the shuttle operational community to make a C&W system upgrade a priority for the recent shuttle Cockpit Avionics Upgrade (CAU) project (McCandless et al., 2003). A CAU project team proceeded to develop software and user interfaces requirements for a more capable Enhanced C&W (ECW) system. ECW software, an extensive collection of rules for interpreting C&W events, essentially automated the root-cause diagnosis process. ECW cockpit interface logic would have suppressed all cockpit alarms and fault messages except those associated with the root cause.

Although the underlying logic to interpret C&W events was fully developed, and the temporal guidelines for message and alarm suppression fully specified, ECW was never instantiated or implemented in simulation, so the performance benefits associated with root-cause determination and annunciation capabilities were never examined. Moreover, the ECW effort was limited by the fact that ECW was designed for a legacy spacecraft and a legacy C&W system. So, for instance, it was deemed "out-of-scope" to attempt to integrate ECW into a more comprehensive fault management support system that would have integrated ECW interfaces with electronic interfaces for fault isolation and recovery.

Nevertheless, it was clear to the operational community that the ECW capabilities were highly desirable requirements for Project Constellation C&W systems. The Constellation Program Crew Exploration Vehicle (CEV) Cockpit Crew Interface Requirements Document (CCIRD) levied two important requirements for Orion vehicle C&W system capabilities over and above the traditional functions:

> ***Root Cause Failure Presentation (Section 3.3.18.2)***
> *Cockpit C&W display formats shall present root cause failures for CEV and other integrated elements.*

Rationale: Presenting the root cause of failures to the crew improves situational awareness.

Failure Impacts Presentation (Section 3.3.18.2)
Cockpit C&W display formats shall present failure impacts as a result of an identified root cause for CEV and other integrated elements.
Rationale: Understanding failure consequences is key to maintaining adequate vehicle-systems-state situational awareness. Presenting failure impacts as a result of an identified root cause improves situational awareness for the crew.

Unfortunately, after these requirements were drafted, further analyses have reduced the allowable mass for the Orion CEV. That reduction is forcing designers to reconsider incorporating Advanced Caution and Warning systems (ACAWS), as these systems may require more onboard computing resources that incur penalties in vehicle weight and in software development, test, and validation schedules. Ideally, the decision whether to proceed with an ACAWS should be informed, not only by the associated weight and software development penalties of such a system but, just as importantly, a firm grasp of the operational benefits of a C&W system with root-cause determination and root-cause annunciation capability.

The primary purpose of the work summarized in this report is to provide quantitative metrics on operator accuracy and response time to work systems malfunctions with and without ACAWS assistance.

1.4. Overview of Human Factors C&W Evaluation

1.4.1. Simulation Infrastructure and Operational Scope

Our ACAWS evaluation was enabled and supported by two integrated software modules. One module, a dynamic flight model of the Crew Exploration/Crew Launch Vehicle "stack" called Antares, provided real-time flight and navigation parameters, such as vehicle position, attitude, and velocity to drive a Primary Flight Display (PFD) described below.

The other module was a real-time Matlab/Simulink model of a generic Electrical Power System (EPS) connected to a set of power-consuming equipment (fans, water pumps, etc.) found in a spacecraft's Environmental Control and Life Support System (ECLSS). The MatLab simulation models a physical hardware-in-the-loop facility at NASA Ames Research Center called the Advanced Diagnostics And Prognostics Testbed (ADAPT). Shown in Figure 1.1, ADAPT consists of three batteries (actually, three pairs of 12 V automobile batteries) and a power distribution system that provides power to two load banks, A and B, each containing multiple forms of powered ECLSS equipment. Figure 1.1 also illustrates the nominal operational mode of the facility, which is to supply power to Load Bank A from Battery A and to Load Bank B from Battery B. Importantly, the ADAPT architecture is complex enough, and contains enough functional redundancies, to generate numerous systems malfunctions with fault isolation and recovery possibilities. For failures of an EPS subsystem, these possibilities included cycling switches that have failed open, switching to backup power sources (e.g., Battery C), or switching to backup ECLSS equipment. In the case of ECLSS equipment failures, there were possibilities to switch to backup (redundant) pieces of equipment.

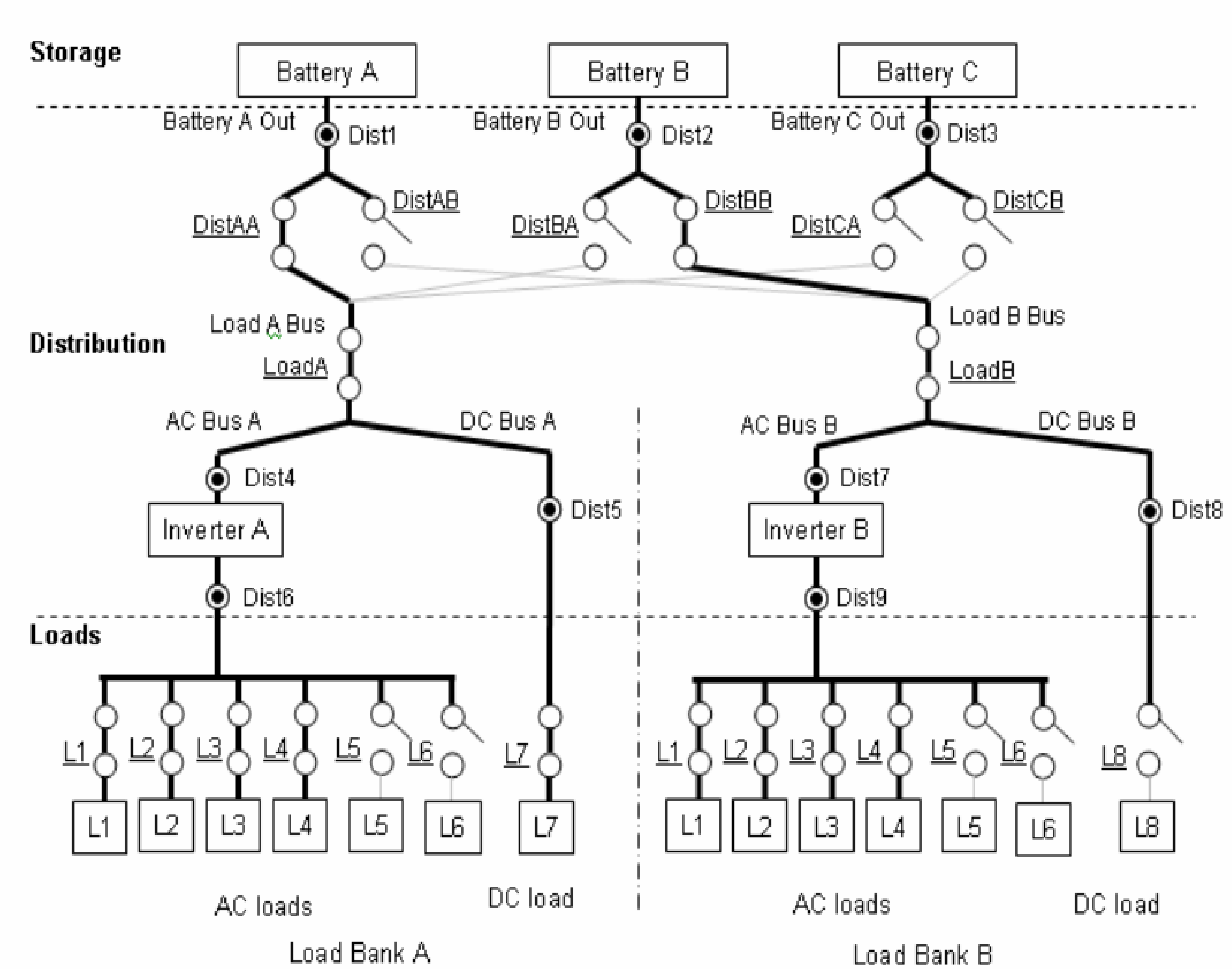

Figure 1.1. ADAPT architecture. The EPS system was divided into storage, distribution, and load regions. Battery A is powering Load Bank A and Battery B is powering Load Bank B. Thick black lines represent powered EPS buses; thin grey lines represent unpowered buses. Each Load Bank contains critical, non-critical, and backup ECLSS pumps and fans.

Both the hardware and simulated versions of the ADAPT facility are fully instrumented with sensors that provide continuous readings of over 100 EPS and ECLSS system parameters including voltages, currents, flows, pressures, and temperatures. Building on this infrastructure, the ADAPT/ISIS team completed three software development projects to enable the facility to support human-in-the loop evaluations of C&W systems. First, a limit-sensing software module was developed and validated. To that end, the ADAPT hardware was operated many times under nominal conditions so that the data associated with nominal functioning could be recorded and characterized. ADAPT was then further operated in off-nominal operational modes (i.e., with switches turned off, loads turned off, etc.) to capture the sensor values generated when components and subsystems were non-operational. These results were used to develop empirical limits for nominal operation, and to provide the parameters for the limit-sensing software. Once the limits were determined, out-of-limit values were then associated with a table of fault messages and alarms for display to the operator. Last but not least, an extensive library of fault isolation and recovery procedures was generated, validated operationally, and then added to an electronic database for display on an electronic procedure viewer.

1.4.2. Operations Environment and Crew Interfaces

We employed this simulation infrastructure to evaluate the performance impacts of selected C&W system capabilities in part-task simulations of the launch-to-orbit (ascent) phase of OCEV mission. Participants, virtually all instrument-rated general aviation pilots, were seated in front of an 11” by 17” touch-sensitive monitor in portrait (vertical) orientation.

The real estate on the monitor was divided into equal upper and lower sections. The upper half of the monitor was reserved for a primary flight display (PFD; see Figure 1.2) that included a suite of shuttle-derived flight indicators (e.g., an attitude display “eyeball” and horizontal and vertical

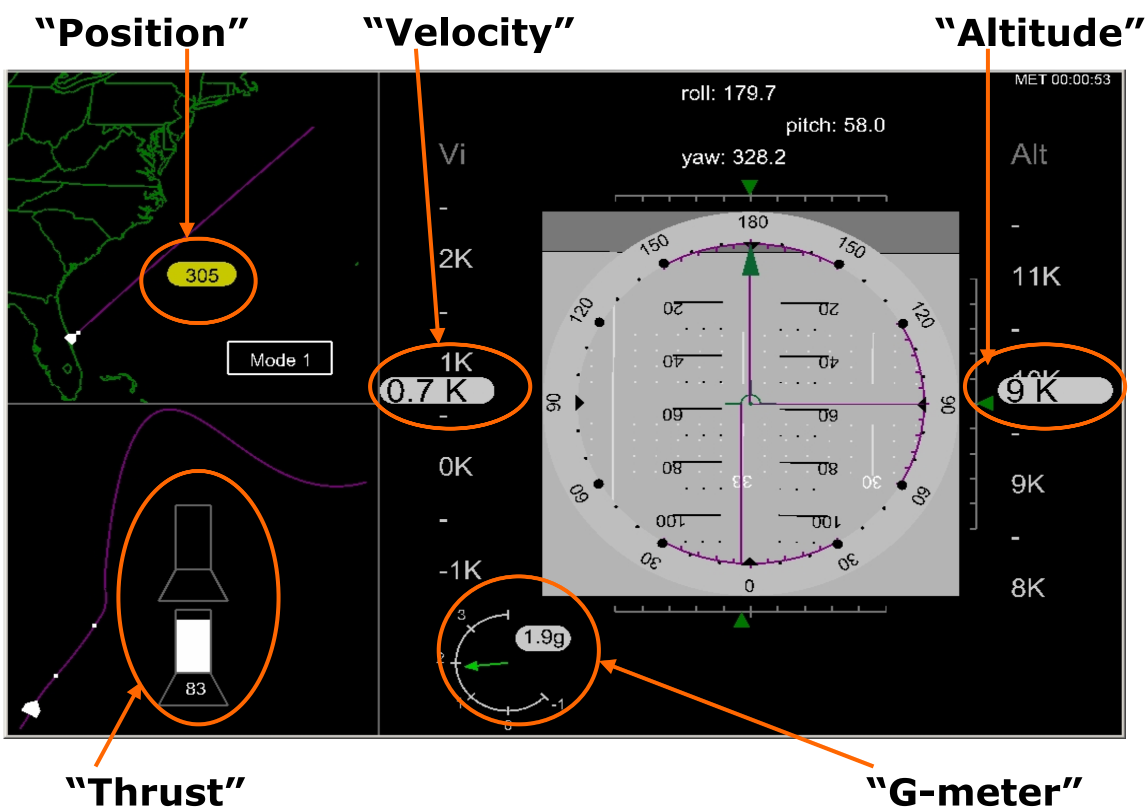

Figure 1.2. PFD and associated flight task. The upper left portion contained a notional horizontal situation display; the bottom left portion, a notional vertical situation display; the right side contained an attitude director indicator and associated flight-related vehicle parameters. Every 20 sec, on average, one of the circled parameters turned yellow. Participants were instructed to make a speeded response to the color change by touching the location of the parameter on the screen and calling out the parameter’s name. If the screen did not record a physical touch on the parameter within 5 sec, the parameter turned red for an additional 5 sec. In the Figure, the parameter “Position,” a scaled value corresponding to vehicle longitude, has turned yellow.

situation indicators), vehicle velocity and altitude tapes, a G-meter, first and second stage thrust indicators, and a Launch Abort System separation indicator.

A straightforward task was embedded in the PFD to assess participants' capability to divide their attention between flight monitoring and systems health management tasks, and to investigate the impact of working a systems malfunction on flight monitoring with and without ACAWS assistance. Following the simulated liftoff of the ascent stack, every 20 sec (on average), the interior of the box surrounding one of the parameters on the PFD changed color from white to yellow (for five seconds) and then to red (for an additional five seconds). When participants noticed a parameter box change color, they were instructed to, as quickly as possible, reach up with their right index finger and press the indicator directly while calling out its name (for example, if the G meter box changed color, they would press the meter position on the touch screen and call out "G"). This action returned the indicator color back to white ("nominal"). Furthermore, the participants were asked to perform a nominal call out when they detected the transition from the first stage to the second stage (by saying "Stage 2") and the transition from abort Mode 1 to Mode 2 (by saying "Mode 2").

The lower half of the monitor was devoted to the user interfaces for systems monitoring and fault management. Two suites of interfaces were included in the evaluation. We will start by describing the display interfaces that were common across the two display suites, followed by the customized interfaces.

1.4.3. Crew-vehicle Interactions

On Constellation Project vehicles such as the OCEV, we noted earlier that during dynamic flight phases, such as ascent, crew interactions with the vehicle will be through a hand controller. Accordingly, we designed our interfaces so that all required forms of crew-vehicle interaction could be completed via a hand controller (a commercial gaming device produced by Nostromo) operated by the seated participant's left hand (Figure 1.3). The devices on the controller that were used in our study were a set of four arrow keys, an "enter" key, and an orange button. The button was programmed as an operational shortcut to extinguish visual and auditory alarms. Duplicate functionality for silencing the alarms was available through an edge key label. The four arrow keys allowed the user to navigate (2-D) through selectable (hereafter, "tab-able") features on the glass displays. The peripheral tab stops corresponded to edge key labels arranged along the four edges of the displays, while the interior tab stops corresponded to functions inside

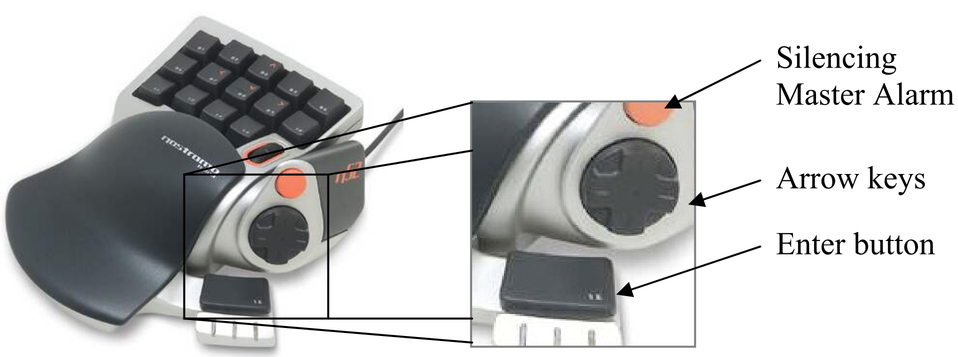

Figure 1.3. Nostromo Hand Controller

a display format. When the current focus was on an edge key label, pushing the arrow keys moved the focus around the peripheral tab stops. When the operator needed to transition the tab focus to tab stops inside a display format, he or she moves the current focus to an edge key label, which enables the transition. Selecting that label by pressing enter on the hand controller shifted focus to a default interior tab stop inside the display. To support the reverse process (i.e., returning focus to the edge key labels), all display formats contained an interior tab stop labeled "Return to Edge Keys". The operator would simply navigate to (move interior focus to) the "Return to Edge Keys" interior tab stop and click the "Enter" key on the hand controller. The tab focus then shifted back to the last peripheral edge key label to have focus.

1.4.4. Lower Display

1.4.4.1. Fault Sum. The default lower display (i.e., the display up at the beginning of each experimental run) was a modified version of the Fault Summary Display developed through the cockpit avionics upgrade (CAU) project for the shuttles. Shown in Figure 1.4, the display provided "at a glance" information on the health and operational status of key components of the EPS and ECLSS systems. Values depicted in bright white are nominal; values colored red or yellow are associated with off-nominal sensor readings or failed components; and values in gray were not supported by the ADAPT architecture. The figure shows a condition in which sensor values associated with the AC bus connecting Battery B to Load Bank B are off-nominal, and

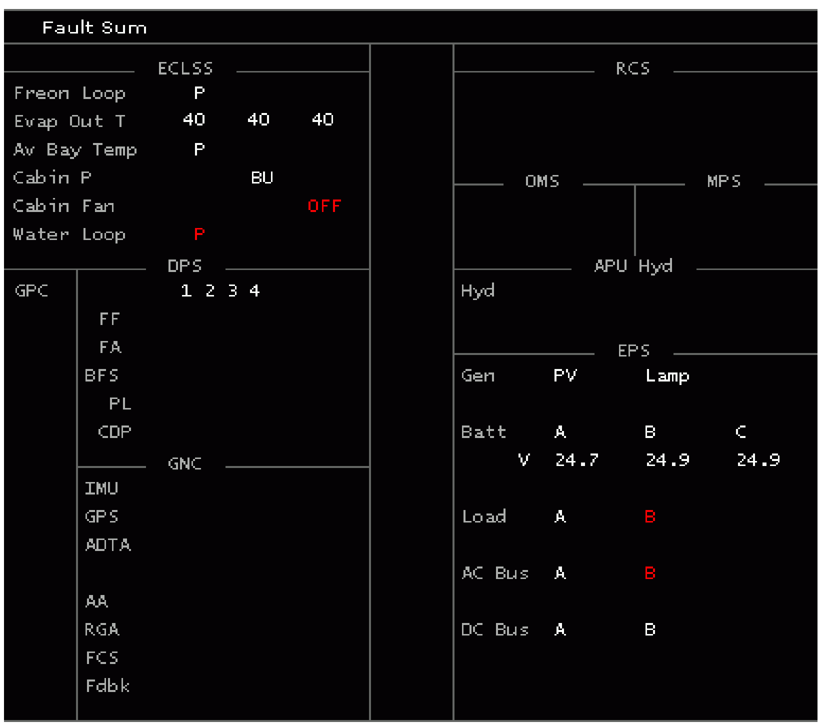

Figure 1.4. Fault Sum Display. The lower right area provides "at a glance" status of essential components of the ADAPT EPS system, such as the batteries, main buses, and load banks. The upper left region depicts status of ADAPT-supported elements of the ECLSS system. Elements coded in red indicate a problem with AC power supply to Load Bank B, with associated Loads failed (Cabin Fan and Water Loop) in the ECLSS system.

Load Bank B loads are color coded red (failed), in the ECLSS section. This pattern provided preliminary information for operators to begin to diagnose the source of the malfunction.

1.4.4.2. Elsie. The suite of user interfaces collectively called "Elsie" (not an acronym), was used to gather baseline measures of performance against which to assess performance impacts of ACAWS and other user interface design concepts. The design philosophy behind Elsie was to utilize as many of the existing shuttle C&W interfaces and features (auditory alarms, fault messages, and "out-of-limits" indications on system summary displays) and CAU display format features as possible, while modifying these as necessary to fit Project Constellation vehicle workstation design constraints and design opportunities. The primary Elsie interface is shown in Figure 1.5. Consistent with the Constellation need to consolidate task-related information on as few display formats as possible, this display format contained three distinct regions. The upper left region was reserved for viewing ADAPT system summary and vehicle commanding displays, such as the virtual switch panel shown in Figure 1.6. The lower region of the display was reserved for caution and warning fault messages and a Master Alarm. The region on the right hand side was allocated to the electronic procedure viewer.

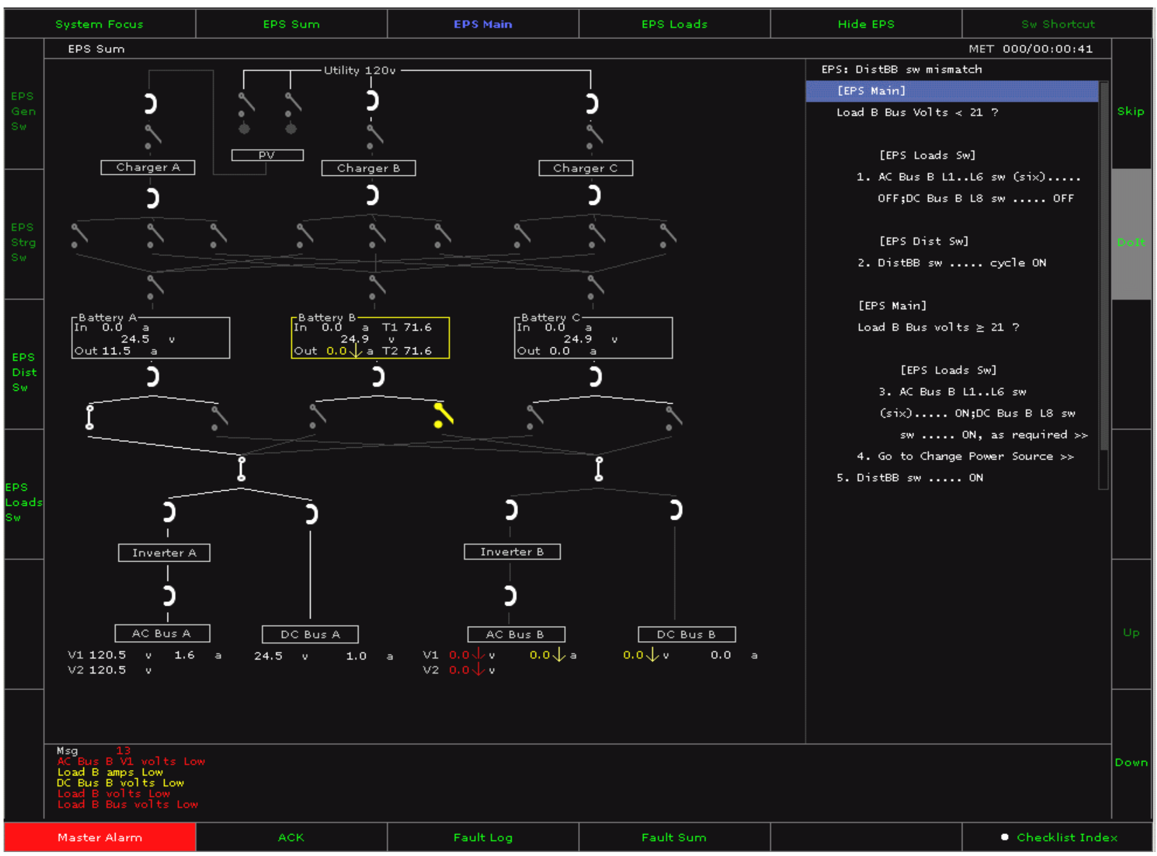

Figure 1.5. Elsie Fault management Display at the outset of procedure navigation. The lower region is devoted to C&W interfaces (fault messages and Visual Master Alarm); the upper left region to system summary and vehicle commanding displays; the right region to the electronic procedures viewer.

Figure 1.6. Elsie Fault Management Display in Vehicle Commanding Configuration. The focus bar in the procedure checklist is commanding a series of switches to be taken to the "off" position on the virtual "EPS Loads Switches" panel. The background of the relevant switches is colored blue to link them perceptually to the focus line in the electronic procedure viewer.

These components functioned together as follows. Soon after a malfunction occurred, a C&W event resulted. The event encompassed off-nominal indications on the Fault Sum display, one or more fault messages in the C&W region of an Elsie fault management display, and an auditory alarm. The Elsie fault management display, shown in Figure 1.5, consolidated all necessary sources of information and electronic commanding interfaces to work ADAPT malfunctions into one integrated display format. The bottom of the display contained the C&W interfaces; one of the soft edge key labels turned red to provide the visual Master Alarm indication; the top left area was reserved for system summary displays and virtual switch panels; and the right hand side was allocated to the electronic procedure viewer. After acquiring information from the Fault Sum display, the natural next step would be to call up the Elsie fault management display format and call up a relevant system summary display in the upper left region. The information from these various sources (system summary display, caution and warning fault messages, etc.) would then be assimilated and processed by the operator to make a root cause determination. Once a determination was made, the operator would then start interacting with the electronic procedures viewer, navigating through a three-level menu (top level: List of Vehicle systems; Middle level: List of systems-specific malfunctions with titles isomorphic with C&W fault messages; Lowest level: checklist of procedures for selected malfunction) until the appropriate checklist was retrieved.

Figure 1.5 illustrates a hypothetical point in a fault management operation in which the EPS SUM display has been selected and is occupying the system summary display region; the red caution and warning Master Alarm indicator has not yet been extinguished by operator acknowledgment (see below); and the appropriate checklist has been brought up in the electronic procedure viewer and the focus (filled blue rectangle) is on the first line of the procedure. As the operator completes each line (step) of the checklist, the focus indicator moves down and completed steps are grayed out and move above the current focus line in the viewer. Eventually, the focus will reach the line marked 1, the first systems reconfiguration command. Just prior to that line, the procedure calls for the operator to bring up a vehicle commanding interface in the top left region. Figure 1.6 illustrates the look of the commanding displays, essentially virtual switch panels that reflect the ADAPT EPS architecture. As shown in the figure, the background of each relevant switch is color coded blue to match the filled background of the current focus line in the checklist. In Figure 1.6, that line is specifying that the seven color-coded switches at the bottom of the "EPS Loads Switch" panel should be turned off. This is accomplished by placing the input device focus inside the EPS Loads Switch" panel (by selecting the "DoIt" edge key label), and pressing the enter switch sequentially for each highlighted switch to toggle its state to the opposite of what is currently displayed. After completing the set of actions specified by this line, the operator chooses "Return to Edge Keys" and informs the procedure viewer that all commands have been completed by navigating to the "Done" edge key label and pressing the "enter" key on the hand controller. The procedure viewer then advances to the next line. The operator navigates back and forth between the switch panel and the procedure viewer in this fashion until the checklist is complete.

To summarize, Elsie contained a host of electronic interface design concepts and concepts for crew-vehicle interaction driven by design requirements for next generation Constellation vehicle workstations. We would expect many performance advantages to accompany these interfaces relative to the more manual interfaces on the shuttles. However, Elsie operators will still face the challenge of diagnosing the faults with essentially the same cockpit indications (fault message proliferation, etc.) as are generated by the shuttle C&W system.

1.4.4.3. Besi. The other suite of displays, called Besi (also not an acronym), had several notable differences from the Elsie interfaces. Most important for present purposes, the Besi display format incorporates an interface with an additional software module called HYbrid Diagnostic Engine (HyDE), a deterministic model-based reasoning system that automates the process of root-cause determination. As shown in Figure 1.7, the lower C&W region of the Besi fault management display format was split into two areas. The area on the right is used to display the same sets of fault messages that were presented on the Elsie interface. The area on the left, the Root Cause List area, is used to display the root-cause diagnosis as determined by HyDE. When the HyDE diagnosis appears (approximately three to six seconds after the malfunction is introduced), the operator performs whatever cross-checks he or she deems necessary to verify or reject the diagnosis. If the operator accepts the diagnosis, he or she can accept it by navigating to the "Root Cause Select" tab underneath the Root Cause List area and pressing "enter" on the hand controller. This action transfers control to the interior Root Cause List area. If multiple root causes are shown, the operator can navigate through the list and select the one to address next. When a root cause is selected (by again pressing the "enter" key), the next unique Besi capability is activated. In particular, a magenta "selected" dot appears beside the root cause message in the Root Cause List area, a magenta box appears around the root-cause component on the EPS summary display and, most importantly, the procedure checklist appropriate for that malfunction automatically appears in the electronic procedure viewer area.

Another notable difference between Besi and Elsi is that Besi integrates vehicle-commanding displays (i.e., the equivalent of Elsie's virtual switch panels) into the schematic display as shown

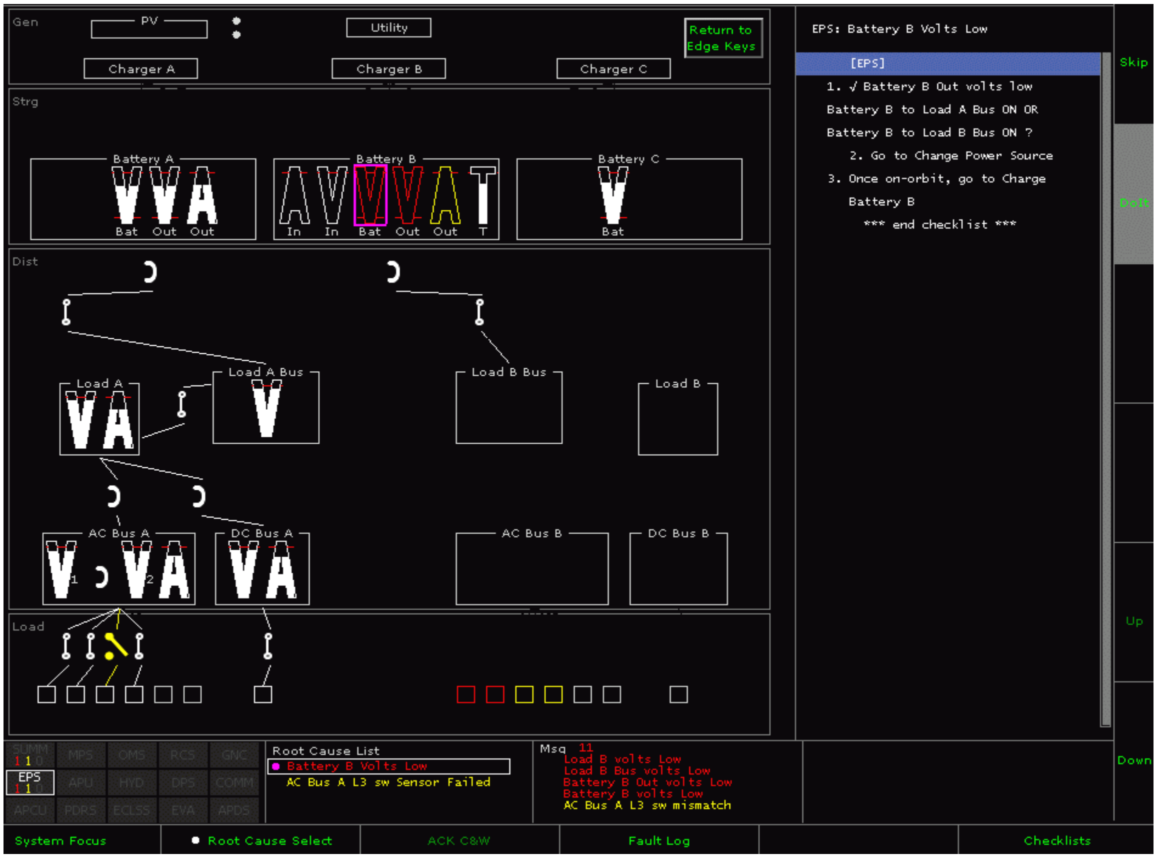

Figure 1.7. Besi fault management interface. Operator has selected the red (most critical) failure in the Root Cause Display Box. The failed element (Battery B volts) is highlighted in the EPS display, and the appropriate checklist is queued up in the procedure viewer.

in Figure 1.7. When a procedure line called for a switch throw, the operator would enter the EPS display via the "Connect" tab in the upper-right corner of the display. This would bring the focus of the hand controller inside the EPS summary display with the default tab stop at the switch specified in the current line of the procedure. (A single line of a procedure could specify a list of switches that need to be thrown. In this case, the default tab stop was the first switch in the list.) A green line highlighted the current focus. When an element was highlighted, pressing the "enter" key on the hand controller toggled its on/off state (e.g. if current state was off, the state was changed to "on").

In summary, Besi can be likened to interactions with a competent vehicle manager. The philosophy behind Besi was to summarize as much information as possible. Details (such as the full list of fault messages generated as part of the C&W event) are available, but hidden from view unless requested by the operator. In contrast, the Elsie interfaces can be likened to interactions with an engineer. The philosophy behind Elsie was to present all available information to the crew and require them to make fault-management decisions (particularly root-cause diagnoses) without a great deal of computer support. In this approach, the crewmember has all the details regarding what components of the EPS and ECLSS systems failed, and had the responsibility of integrating all relevant information to make a root cause determination of the problem.

1.4.5. Evaluation Overview

The design of the study was straightforward. Each participant completed two series of seven simulated CEV/CLV ascents each, one series with the Elsie interfaces, the other with the Besi interfaces. On each ascent, one or more EPS and/or ECLSS malfunctions were introduced shortly after launch. The participant's tasks were 1) to perform the PFD monitoring task and 2) to diagnose the root cause of the C&W events associated with the malfunction(s) and complete the appropriate set of procedures. Participants were told that each task was equally important and that they should work the malfunction as quickly and accurately as possible, while still monitoring the PFD diligently so that they could detect each PFD event. Workload and empirical measures of situation awareness were collected after each run.

Our primary interests were in measuring and directly comparing the accuracy with which participants made root-cause diagnoses with Elsie and Besi interfaces, how long they took to make correct diagnoses, how well they performed the PFD task, and the workload they associated with these activities. In addition, eye movement were recorded to determine whether the Besi interfaces promoted more efficient attention sharing between the fault management (lower) displays and the PFD (upper) display.

2. Evaluation Methodology

The usability evaluation of Elsie vs. Besi was conducted using the ISIS lab CEV Orion simulator. Eight instrument-rated pilots participated in the study. This section summarizes the details of the evaluation method.

2.1. ISIS Orion Simulator Facility

The Intelligent Spacecraft Interface Systems (ISIS) laboratory's CEV Orion simulator was used for the evaluation. The simulation hardware consisted of a Hewlett Packard XW9300 workstation with two dual-core 2.4GHz AMD Opteron processors, 2GB of system memory, and an NVIDIA Quadro FX3450 video card with 256MB of memory running Windows XP Professional. The video card drove two 20-inch touch-sensitive Apple cinema displays, one of which was used by the experimenter and the other by the participant. Figure 2.1 shows the display used by the participant (the display unit on the right was not used). The experimenter's display was located outside the simulator room, and enabled the experimenter to control the experiment and data-collection processes without being seen by the participant.

Simulated vehicle flight dynamics were provided by the Orion Flight Model System via the Antares flight model developed at NASA Johnson Space Center. The Orion Flight Model was housed on a SUN Fire V40z Server, with 2 dual-core 2.4Ghz AMD Opteron processors, and 16GB of system memory. This system communicated flight parameters to the PFDvia a 100Mbps TCP/IP connection.

All EPS and ECLSS parameters were computed by a Matlab (version 7.4.0) and Simulink (version 6.6.1) real-time simulation of the ADAPT facility. On Besi runs, the Hybrid Diagnostic

Figure 2.1. CEV Orion Simulator.

Engine ("HyDE") performed root-cause determinations and interfaced with the C&W system to show just the root cause fault message in the Root Cause List area.

The flight parameters and EPS/ECLSS parameters computed by these simulators were sent to the Primary Flight Display (PFD) and Elsie/Besi display in front of the participant, via a CEV Orion Simulator architecture. In addition, the CEV Orion Simulator sent audio signals to the speaker system installed in the simulator room to provide spacecraft engine noise and Caution & Warning alarms. Figure 2.2 illustrates the CEV Orion simulator architecture.

The CEV Orion simulator is equipped with a custom eye-and-head-tracking hardware (ISCAN ETL-500 eye tracker integrated with Polhemus head tracker). The trackers were mounted on a baseball cap to be minimally invasive. The eye-and-head tracker computed the participant's gaze point with up to 60 Hz of temporal resolution, and approximately .5 inch of spatial resolution. During the simulation trials, the CEV Orion simulator recorded participant's eye-movement data, Elsie/Besi display user commands, PFD color changes, and touch-screen responses to the PFD task. In addition, two Panasonic digital video recorders, two video overlay units (designed by Decade Engineering), a shot-gun style microphone with amplifier, and two NTSC video monitors were used to record the audio visual data of the trial (the participant's face was not on the video camera to protect their identity).

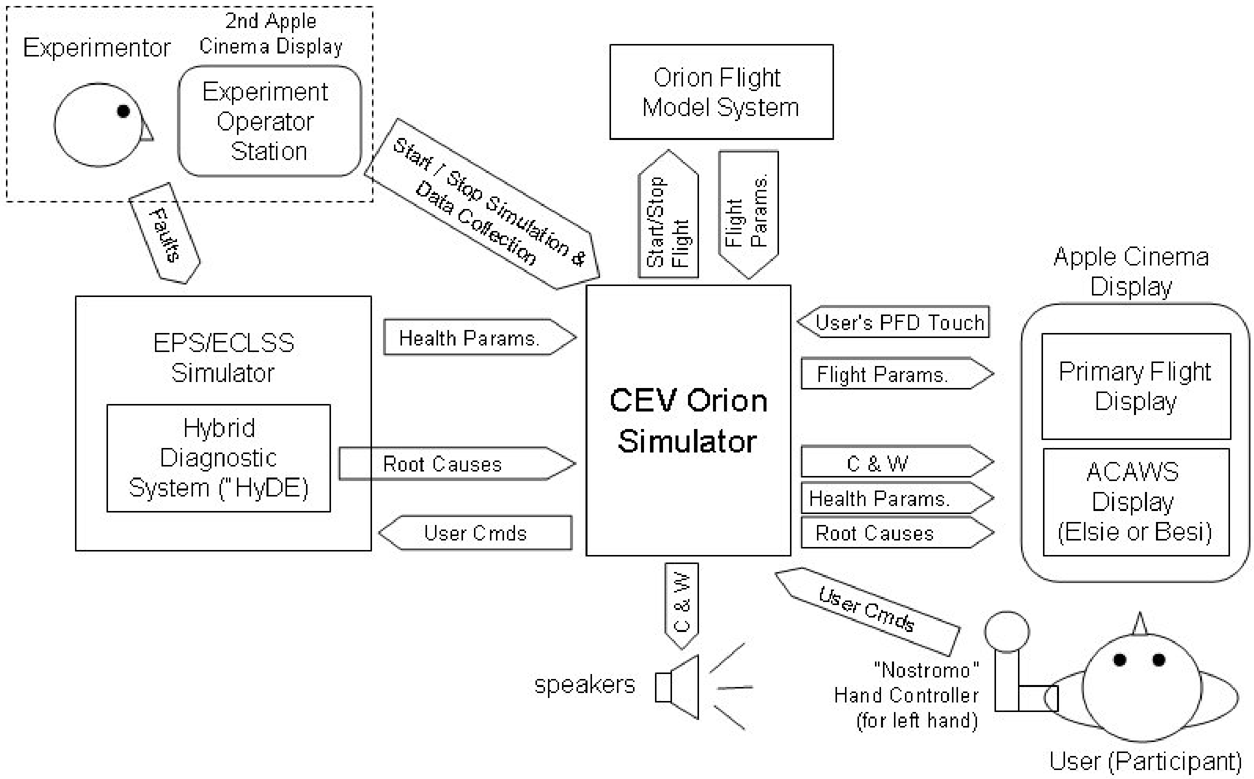

Figure 2.2. CEV Orion Simulator Architecture.

2.2. Participants

Eight participants, seven males and one female, were recruited for the study. We specifically recruited general aviation pilots who met the Federal Aviation Administration (FAA) currency requirements for flight solely by instruments (i.e., no visual cues external to the aircraft). We recruited instrument-rated pilots due to their demonstrated ability to share attentional focus among multiple information sources. We required that they were current according to the FAA rules (performed at least six instrument approaches, one holding procedure, and intercept and track courses through the use of navigation systems all under actual or simulated instrument-flight conditions within the last six months) for assurance that they maintained that ability after initially receiving their rating. All but one pilot were instrument current. The one exception was a Certified Flight Instructor - Instrument (CFII: necessary license to instruct instrument flying) with total flight time of over 3000 hours, of which about 200 hours were solely by instruments. Even though he was not instrument current at the time of the data collection, his past experience with instrument flight suggested that his scanning skills would be comparable to the other participants.

The participants' ages ranged from 24 to 54 years (the average 37.5). Their total flight times ranged from 230 to 21000 hours, and the instrument-flight times ranged from 68.2 to 2000 hours. The seven current instrument-rated pilots had the last instrument flight within the last four months. All participants were right-handed, and had normal or corrected vision (20/40 or better).

2.3. Training and Testing

Prior to the data collection, each participant received approximately twelve hours of training. The general training procedure was as follows:

1) A two-hour assignment to read Volume 1 of a training manual. This volume describes the overview of CEV Orion ascent operation and the details of the ADAPT architecture, including the EPS and ECLSS. (See Appendix for the copy of the training manuals.)
2) A one-hour in-class PowerPoint presentation to review the contents of Volume 1.
3) A one-hour in-class PowerPoint presentation to describe the display features of Elsie and Besi interfaces.
4) A three-hour "hands-on" practice session using a lap-top-based part-task trainer. In each session, the participant completed, with instructor assistance, five basic malfunction management scenarios with the instructor's help with the Elsie interfaces, followed by the same five malfunction management scenarios with the Besi interfaces. Then, with minimal instructor assistance, the same scenarios were repeated for Besi then Elsie.
5) An additional hour of hands-on training using the lap-top trainer. Each participant completed five additional fault management scenarios which were different from the ones used in the step 4) for Elsie and Besi with minimum help from the instructor. The display orders were counterbalanced between Elsie and Besi to reduce the training bias between the two displays (i.e., three Elsie trials followed by five Besi, then two more Elsie trials.)
6) A two-hour assignment to read Volume 2 of the training manual. Volume 2 (also included in Appendix) summarizes the Elsie and Besi display features learned in the hands-on practice.

Each training manual included "Self-Check Quiz" sections, which tested the participant's understanding of the important points. The answers to the self-check quiz questions along with brief explanations were provided at the end of each volume to help the participant's self study. The same questions were posed again in a final exam taken by participants immediately prior to their data collection sessions. If a participant answered a question incorrectly, the instructor briefed the participant about the correct action until the participant understood it. The final exam also served as a screening for participants whose understanding was insufficient to adequately perform the fault management task. If the instructor assessed that that was the case, the participant was asked to withdraw from the study. As a result, one participant was excused from the study and replaced.

After the participant passed the final exam, he/she was directed to the CEV Orion simulator room, where, first, two practice runs, duplicates of the training sessions, were completed. Then, the PFD was brought up on the top half of the monitor, and the participant was given an opportunity to practice the PFD touch-and-call-out task (i.e., the color change call-outs and nominal call-outs). Once the participant felt comfortable with the PFD task, a full "dress rehearsal" was completed, consisting of the participant performing the PFD and malfunction management tasks together while outfitted with the eye-and-head tracker cap. The data collection phase of the study then commenced.

2.4. Data Collection

Data collection was split into two sessions. Each session consisted of seven simulated ascents with one display format suite (either Elsie or Besi). Half of the participants completed seven

“Elsie ascents,” in the first session followed by seven “Besi ascents” in the second session. For the other half, the session order was reversed. Scenario orders were also counterbalanced across participants as described below.

Table 2-1 lists the fourteen malfunction scenarios used and their correct procedures. Scenarios #5 (DistAA sw mismatch) and #6 (DistBB sw mismatch) were symmetric and used as a pair in this study. That is, each participant who was assigned scenario #5 on Elsie was assigned Scenario #6 on Besi and vice versa (#5 on Besi and #6 on Elsie). Using slightly different procedures but with similar difficulty for Elsie and Besi for the same participant helped compare Elsie and Besi performance directly while minimizing potential learning effects. The other pairs were scenarios #7 and #8, #9 and #10, and #13 and #14. Scenarios #11 and #12 were identical. Scenarios #1 through #4 formed one group that provides 2 x 2 conditions, the real failure vs. sensor failure and single malfunction (lower workload) vs. multiple malfunctions (higher workload). For each participant, Scenarios #1 and #3 were run with the same display (Elsie or Besi), and Scenarios #2 and #4 were run with the other display.

Table 2-1. Malfunction Scenarios

Scenario #	Malfunction(s)	Correct Malfunction Management Procedure(s)
1	A/L1 sw mismatch	Turn on backup (B/L5)
2	B/L1 sw mismatch (sensor failure)	Do nothing
3	1) Load B sw mismatch (restorable), 2) A/L2 sw mismatch (sensor failure)	1) Cycle Load B sw, 2) Do nothing
4	1) Load A sw mismatch (restorable), 2) B/L2 sw mismatch	1) Cycle Load A sw, 2) Turn on backup (A/L6)
5	DistAA sw mismatch (restorable)	Cycle DistAA sw
6	DistBB sw mismatch (restorable)	Cycle DistBB sw
7	Battery A volts low	Change power source Battery C to Load A
8	Battery B volts low	Change power source Battery C to Load B
9	Inverter A failure	AC bus A loss
10	Inverter B failure	AC bus B loss
11	1) Inverter A failure, 2) Battery A volts low	1) AC bus A loss, 2) Change power source Battery C to Load A; Alternatively, 2) Turn on backup DC load, B/L8
12	Same as 11	Same as 11
13	1) Battery A volts low, 2) Battery B volts low	1) Change power source Battery C to Load A, 2) Change power source Battery C to Load B (shed all non-critical loads); Alternatively, 2) Combine power sinks onto Load A
14	1) Battery B volts low, 2) Battery A volts low	1) Change power source Battery C to Load B, 2) Change power source Battery C to Load A (shed all non-critical loads); Alternatively, 2) Combine power sinks onto Load B

To simplify the experimental design, the eight participants were divided into four groups of two participants each. Groups 1 and 3 were assigned the Elsie condition followed by Besi; Groups 2 and 4 received the reversed order. The scenario order for Group 3 was the reverse of Group 1. Similarly, the scenario order for Group 4 was that the reverse of Group 2. This arrangement ensured that display order and scenario order were fully counterbalanced to minimize any potential learning and fatigue effects.

During all simulation trials, participants' Besi/Elsie commands (edge key navigations, checklist navigations, switch throws, etc.) were recorded along with their time stamps. Likewise, participant's touches on the PFD and associated timestamps were recorded. The eye-and-head tracker collected their gaze points (i.e., the x and y coordinates on the monitor).

2.5. Data Collection Runs

2.5.1. Procedure

At the beginning of each data collection run, participants were seated in a dimly lit simulation room in front of the display monitor. The display was approximately 20 inches in front of the participant and was adjusted individually so that the eye height was approximately at the middle of the screen. Participants' left arms rested on an armrest. The Nostromo hand controller was positioned on the armrest in a location that allowed participants' left hand to rest comfortably atop the controller.

Immediately prior to each run, an experimenter administered a short eye-movement calibration procedure. Following completion of the procedure, the experimenter left the simulation room and initiated the ascent simulation. Participants were instructed to monitor (scan) both the PFD, so that they could react and quickly and accurately as possible when a parameter changed color, and the Fault Sum display to evaluate EPS and ECLSS system state and status. Approximately 15 sec after liftoff, a malfunction was introduced, followed approximately 1 min later by a second malfunction on multi-malfunction (high-workload) runs. When the alarms occurred, participants entered a "dual task" mode, evaluating and working the malfunction while simultaneously responding to the PFD task. During training, they were told to give equal priority to the PFD task and the malfunction.

Each run had one of three durations. If the malfunction procedures were completed within 8 min after liftoff, the run was ended at 8 min. If the participant completed the malfunction(s) between 8 and 10 minutes after liftoff, the run was ended at 10 minutes. Otherwise, the run ended at 12 minutes.

Immediately following the end of each run, the experimenter entered the simulation room and completed another short calibration procedure. The experimenter then increased the room illumination and presented the participant with paper materials to fill out, including questions about the nature of the malfunction such as what the root cause of the malfunction was, what the impacts were, and self-ratings concerning their performance. Immediately following the completion of this paperwork, TLX and Bedford workload scales were administered via a computer interface.

Following the last run of each session, participants provided their TLX workload weightings via an electronic questionnaire. After completing both sessions, they provided written answers to questions regarding display usage, display preference, and user interface design.

2.5.2. Collected Data

The Human Factors evaluation of the Elsie and Besi concepts encompassed four primary metrics: fault management accuracy and response time, objective assessments of situation awareness, subjective assessments of workload, and participants' eye movements.

2.5.2.1. Fault Management Accuracy and Resolution Time. The purpose of the malfunction management procedures is to bring the vehicle configuration to the appropriate one to recover from or mitigate the given fault situation. Thus, the final ADAPT switch configurations were the natural thing to look at to determine the participant's performance accuracy. It is certainly possible to arrive to the correct final switch configurations without following the proper checklist. However, even a situation seemingly obvious may still contain sensor failures or more complex hidden failures. Also, certain switches need to be thrown in certain order to avoid damaging vehicle components. Thus, it is imperative for cockpit operator to follow the checklist all the time. Based on this viewpoint, the checklist the participants used were also kept tracked, and during the training, the participants were specifically instructed to follow the checklists always. Thus, our strict accuracy criteria were 1) the correct final switch configurations, and 2) all relevant checklist procedures being executed, in the correct order, with no errors of commission.

To assess the accuracy of the fault management, for each trial, the operator's malfunction management performance was classified into the three categories, *Correct*, *Good*, and *Failed*, in the following manner (see Figure 2.3). If any of the final switch configurations were incorrect, or if any of the proper checklists for the given situation were not used, the trial was categorized as

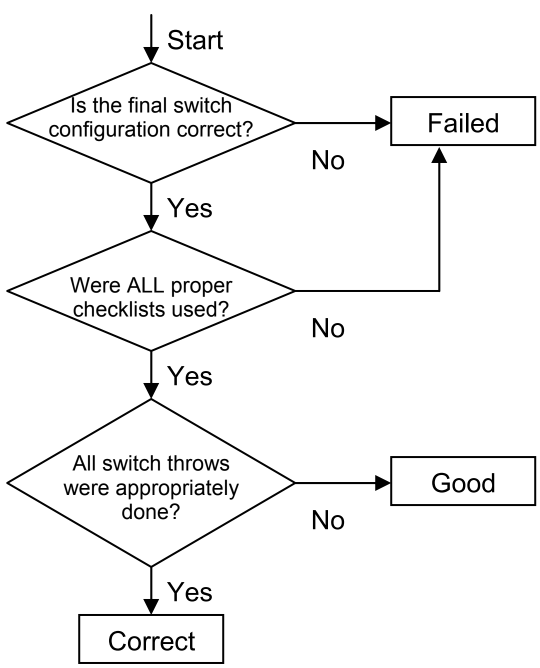

Figure 2.3. Malfunction Management Accuracy Categorization Flow

Failed. Note, again, that if the participant skipped any of the proper checklists, the trial is categorized as "*Failed*" even if the final switch configurations were correct. Note that skipping an essential checklist happens more frequently in Elsie, than in Besi, as the checklist navigation is automated in Besi. However, this illustrates an advantage of the Besi concept, i.e., Besi is designed to help crew navigate to the proper checklists by automating the process. The *Good* category consists of trials in which all the final switch configurations are correct, and all proper checklists were used, but some switch throws were performed inappropriately. For *Good trials,* performance fell slightly short of *Correct*, the perfect, clean performance. For instance, trials where some wrong switches were momentarily turned on/off, or the backup critical loads were turned on before the proper non-critical loads were shed were categorized as *Good*.

An additional measure of performance was fault resolution time (RT). RTs were calculated as the time that elapsed from when the malfunction annunciated through the C&W system, to the completion of all applicable procedures as specified in the appropriate section of the electronic procedures viewer.

2.5.2.2. Situation Awareness. Situation awareness is a measure of a crewmember's understanding of his or her environment. "Good situation awareness" is commonly inferred when a crewmember's actions effect progress toward successful completion of tasks, whereas "poor situation awareness" is inferred when one's actions are not successful. However, it is also possible that one may achieve one's goals (i.e., have good performance) simply through a combination of serendipitous events. To accurately assess situation awareness, we measured crewmembers' understanding of their environment through objective questions with definitive right or wrong answers.

2.5.2.3. Workload. Workload is defined as the mental and physical effort necessary to perform a task. Workload was measured using NASA Task Load Index (Hart, 1988) and the modified Bedford Scale (Roscoe, 1984; Huntley, 1993). Participants rated their workload on both scales following each run.

NASA TLX is a two-part method for quantifying workload. The first part of TLX is a *rating* of six different workload components (on a scale of 1-20): mental demand, physical demand, temporal demand, performance, effort and frustration. Each participant rated each TLX component following each run. Figure 2.4 shows the six slider scales provided on a touch-screen computer monitor to collect the participants' ratings.

The second part of TLX is a *weighting*. After all seven data collection runs for Elsie or Besi were complete, participants made pair-wise comparisons by selecting which TLX component of each possible pair (such as mental demand versus physical demand) was more important to their experience of workload. With six different components, there were 15 pair-wise comparisons, and each component could be selected anywhere from 0 to 5 times. Once the participants completed these pair-wise comparisons, we tallied the number of times each component was selected (with a possible range of 0 to 5 for each tally); this tally formed the weighting for that component. The overall TLX workload for each run was computed as the sum of each component's rating multiplied by its weighting, and the final TLX workload was scaled from 0.5 to 10.

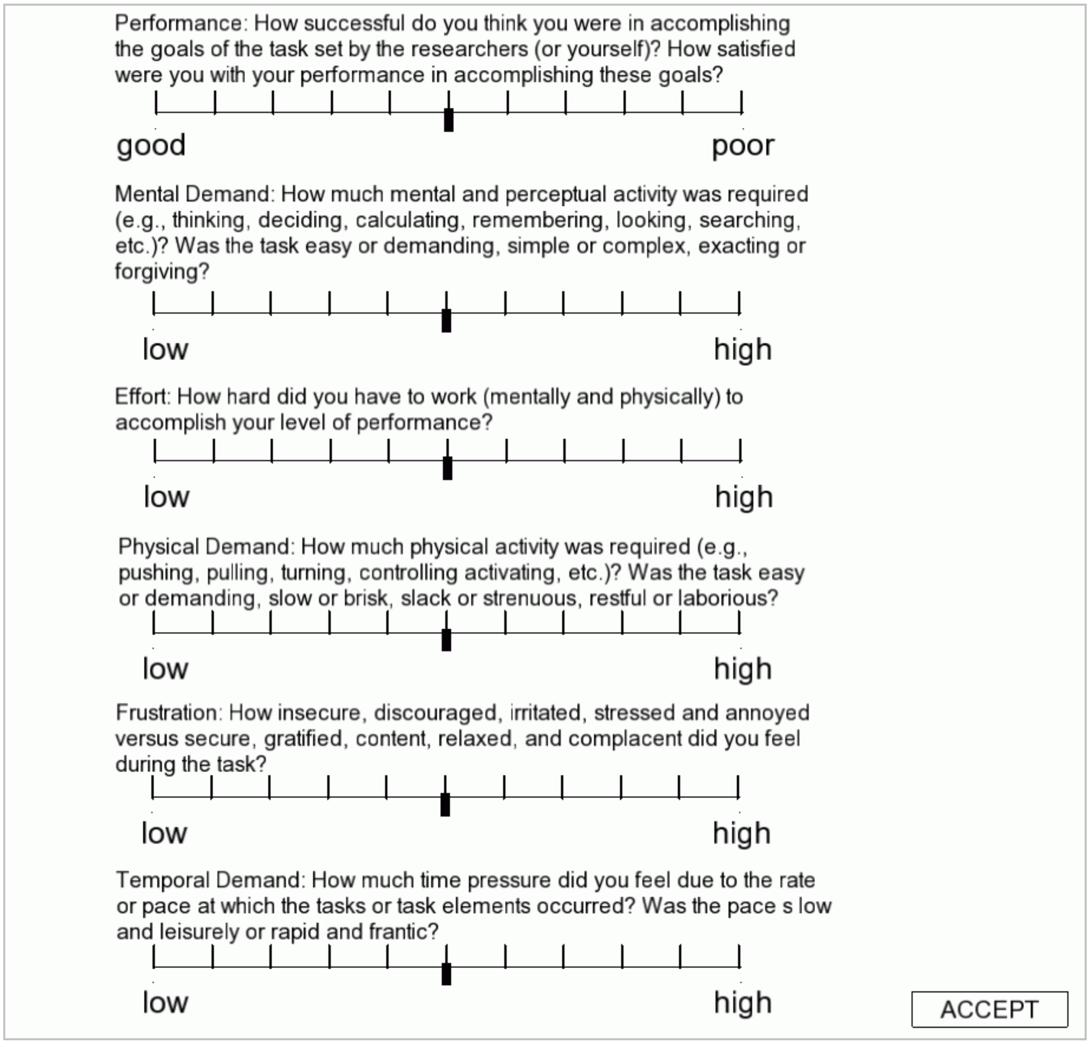

Figure 2.4. TLX Rating Page

The modified Bedford Scale is a 10-point rating scale similar to Cooper-Harper scale. Figure 2.5 shows the modified Bedford scale rating page shown on the touch-screen computer monitor. On this page, the participant started from the bottom, and answered the questions on the left-hand side. Then, the participant selected the appropriate scale for the trial by pressing the number on the right-hand side.

2.5.2.4. Eye Tracking. We used the ISCAN ETL-500 eye tracking and Polhemus head tracking system running in Eye Angle mode. After a participant-specific calibration, the ISCAN software uses the 6 degree of freedom head tracker data plus the pupil and corneal reflection horizontal and vertical positions to compute the participant's gaze location with respect to pre-defined planes. For our analysis, we converted this output data to x-y position relative to our display.

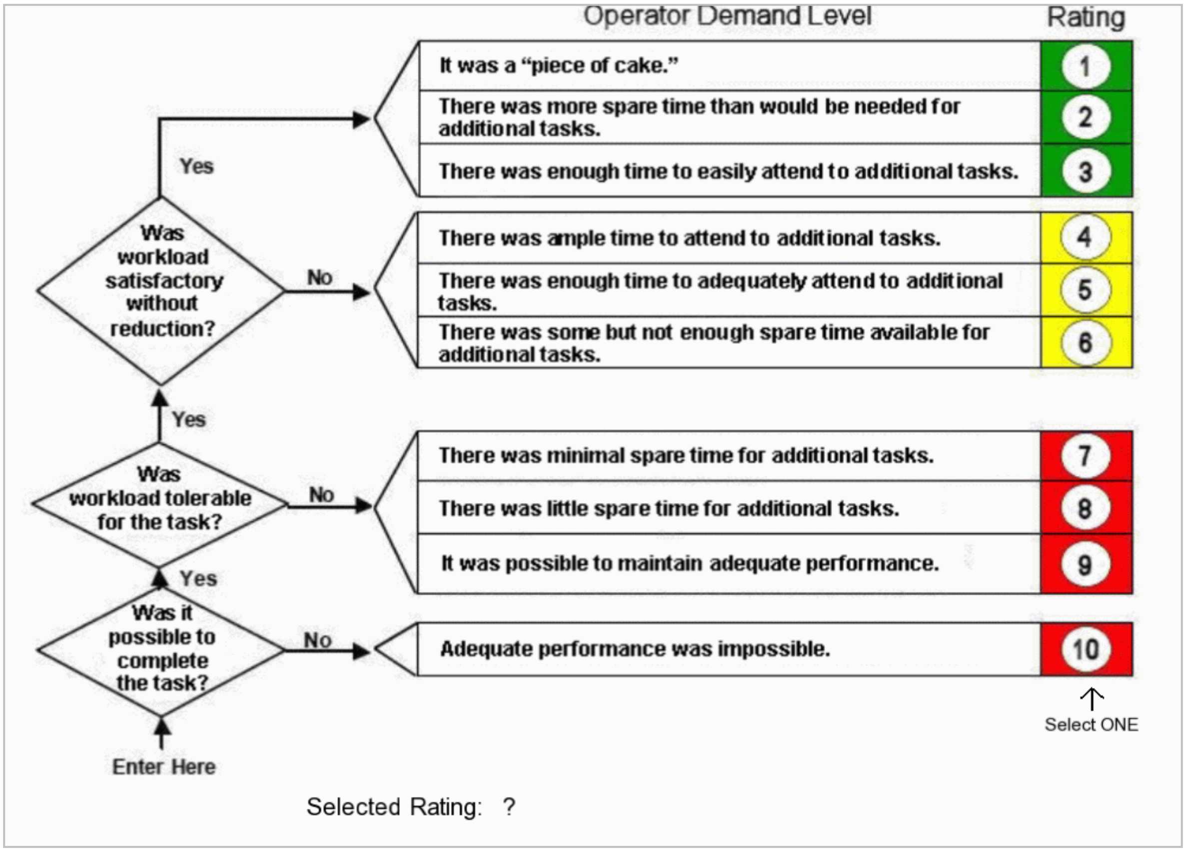

Figure 2.5. Modified Bedford Workload Scale

Calibration Procedures. Immediately before each trial, the ISCAN ETL-500 eye tracking and Polhemus head tracking system was calibrated using ISCAN's standard internal calibration procedure. Each calibration was then verified by having participants gaze at a 3 x 6 grid of equally spaced fixation targets with the eye-tracker output x-y location superimposed. If the calibrated output did not accurately match the fixated locations, the ISCAN calibration was repeated until a good calibration was obtained. Then, in a subsequent external calibration procedure, each point of the 3 x 6 grid was displayed sequentially. After fixating each location, the participant pushed a button, which initiated a 2 second recording, and then displayed the next point. These data were saved for later use in additional off-line calibration. In addition after each trial was complete, this external calibration procedure was repeated.

3. **Results**

3.1. Malfunction Management Accuracy

The categorization results are listed by each scenario in Table 3-1. The total numbers at the bottom indicate that Besi generally had more *Correct* trials (one-tailed binomial t-test, $p < 0.05$) and fewer *Failed* trials (one-tailed binomial t-test, $p < 0.03$) than Elsie. Scenarios #5 through #10 are single malfunctions, and the majority of participants performed them correctly (*Correct*). These trials will be looked into further in the malfunction-resolution-times and eye-movement data analyses.

Table 3-1. Malfunction Management Procedure Accuracy by Scenario

		Elsie			Besi		
Scenario #	**Malfunction(s)**	Correct	Good	Failed	Correct	Good	Failed
1	A/L1 sw mismatch	2	1	1	3	1	0
2	B/L1 sw mismatch (sensor failure)	3	0	1	3	1	0
3	1) Load B sw mismatch (restorable), 2) A/L2 sw mismatch (sensor failure)	1	0	3	3	0	1
4	1) Load A sw mismatch (restorable), 2) B/L2 sw mismatch	3	0	1	4	0	0
5	DistAA sw mismatch (restorable)	4	0	0	4	0	0
6	DistBB sw mismatch (restorable)	4	0	0	4	0	0
7	Battery A volts low	3	0	1	3	0	1
8	Battery B volts low	4	0	0	3	0	1
9	Inverter A failure	4	0	0	3	0	1
10	Inverter B failure	4	0	0	4	0	0
11	1) Inverter A failure, 2) Battery A volts low	2	0	2	2	2	0
12	Same as 11	0	2	2	1	0	3
13	1) Battery A volts low, 2) Battery B volts low	2	0	2	4	0	0
14	1) Battery B volts low, 2) Battery A volts low	0	2	2	2	2	0
	Total	36	5	15	44	5	7

Scenarios #2 and #3 tested the same type of fault (AC bus load switch sensor failure) under single-malfunction and multiple-malfunction conditions, respectively. We were initially concerned that the operator's over-trust in Besi's automation might cause problems when HyDE misdiagnosed the root cause due to, for instance, an incomplete model of the ACAWS facility that caused HyDE to incorrectly diagnose faulty sensor readings. The data, however, did not show such a trend. For the two scenarios with sensor failures (#2 and #3), performance was poorest (the highest number *Failed* trials) with Elsie scenario #3. Although further study is required to investigate the automation over-trust issue more, results of the current study showed no hard evidence of operators over-trusting the automatic root-cause diagnosis software.

Scenarios #11 through #14 were multiple-malfunction scenarios (scenarios #11 and #12 were identical). These scenarios tended to be more complex and lengthy than the single-malfunction scenarios. For these scenarios, we compared Elsie/Besi performance using a Wilcoxon Signed Ranks Test on the individual participant's performance accuracy categories (*Correct* = 2, *Good* = 1, and *Failed* = 0). In scenarios #11 and #12, about the same numbers of the Elsie and Besi trials fell into each accuracy category, and there was no significant statistical difference between these displays. For scenarios #13 and #14, however, Besi performance was significantly more accurate than Elsie ($z = -1.994$, $p = 0.046$).

3.2. Malfunction Resolution Time

We defined the malfunction resolution time (RT) as the time between the first C&W event (i.e., the first C&W message) and the time of the completion of the last item on the checklist. The RT was computed for scenarios #5 through #10 (the single-malfunction scenarios). Most of the participants performed these procedures correctly, and therefore the data were relatively consistent compared to the other scenarios.

We first divided the RTs into five components. The first (and for present purposes, most critical) component is *Diagnosis 1*, during which the operator assesses the situation and makes a root cause determination before going to a particular checklist. Diagnosis 1 starts at the first C&W event and ends when the tab, *Checklist Index* (Elsie) or *Root Cause Select* (Besi), is pressed. The second component is *Checklist 1*, during which the operator navigates to the proper checklist. It starts at the time the tab, *Checklist Index* or *Root Cause Select*, is pressed, and ends when the proper checklist appears on the screen. In Besi, this process is automated, and took only about 0.5 second. The third component is *Diagnosis 2*, during which the operator follows the checklist instructions to perform the diagnosis (troubleshooting the problem in Elsie or double checking the HyDE diagnosis in Besi). It starts when the proper checklist appears on the screen, and ends when the last diagnostic/verification step is acknowledged. The fourth component is *Checklist 2*, during which the operator navigates to the recovery checklist (e.g., change power source, or combine critical power sinks). It starts when the last line of the diagnostic steps is acknowledged, and ends when the recovery checklist appears on the screen. If the procedure does not call for a recovery procedure, the duration of the *Checklist 2* for the trial is set to zero. Finally, the fifth component is *Recovery*, during which the operator performs the recovery steps. It starts at the end of the previous component, either *Checklist 2* or the *Diagnosis 2*, and ends when the last line of the recovery steps is completed.

One of our hypotheses was that assistance from Besi's automatic root-cause diagnosis system (HyDE) would reduce RT by reducing the *Diagnosis-1* durations. Paired t-tests were performed on each participant's *Diagnosis-1* durations for each scenario pair (i.e., #5 and #6, #7 and #8, and #9 and #10). Data from participants whose accuracy was categorized as *Failed* in either member of the scenario pair were excluded from this test. For Scenarios #5 and #6 (DistXX sw mismatch), the *Diagnosis-1* durations were significantly shorter for Besi trials than Elsie ($t(7) = -18.26$, $p < 0.001$, mean durations = 22.2 sec for Besi, 44.0 sec for Elsie). For the Scenario #9 and #10 pair (inverter failure), the *Diagnosis-1* durations were again significantly shorter for Besi

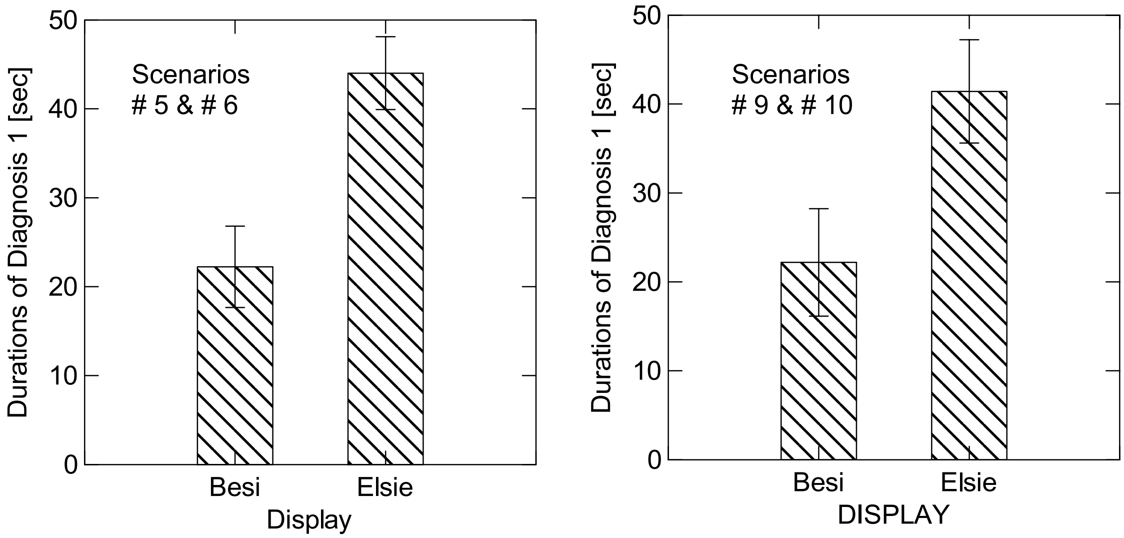

Figure 3.1. Means and Standard Errors of Diagnosis-1 Durations in the Scenarios #5 & #6 (Left) and Scenarios #9 & #10 (Right)

than Elsie ($t(6) = -4.09$, $p = 0.006$, mean durations = 22.2 sec for Besi, 41.4 sec for Elsie). See Figure 3.1 for the means and standard errors. No significant display effect was found for the *Diagnosis-1* durations in the Scenario #7 and #8 pair (battery volts low; not shown in Figure 3.1).

As Figure 3.1 shows, the *Diagnosis-1* durations in Elsie trials are nearly twice as long as those in Besi trials. The similar paired t-tests were applied to the total RTs, and the results indicated that, for the scenarios #9 and #10 (inverter failures), the RTs were significantly shorter for Besi than Elsie ($t(6) = -4.54$, $p = 0.004$, mean RTs = 107.3 sec for Besi, 176.2 sec for Elsie). In this study, no statistical significance was found for the other two scenario pairs (#5 & #6, and #7 & #8). However, the graphs in Figure 3.2, which plot total RTs accumulated across all the participants (except those participants whose trials were categorized as *Failed* in either member of each scenario pair), still show visible trend that Besi tends to result in shorter total RTs than Elsie. One factor is that the *Diagnosis-1* durations tend to be shorter with Besi. The other factor is that the Besi's function to automatically bring up the proper checklist greatly shortens the durations of the *Checklist 1* and *Checklist 2*. Figure 3.2 suggests that these effects collectively make the total RT shorter in Besi trials than Elsie. The durations of the *Diagnosis 2* and *Recovery* are determined by the length of the checklists, and thus, seem to depend on the type of the procedure.

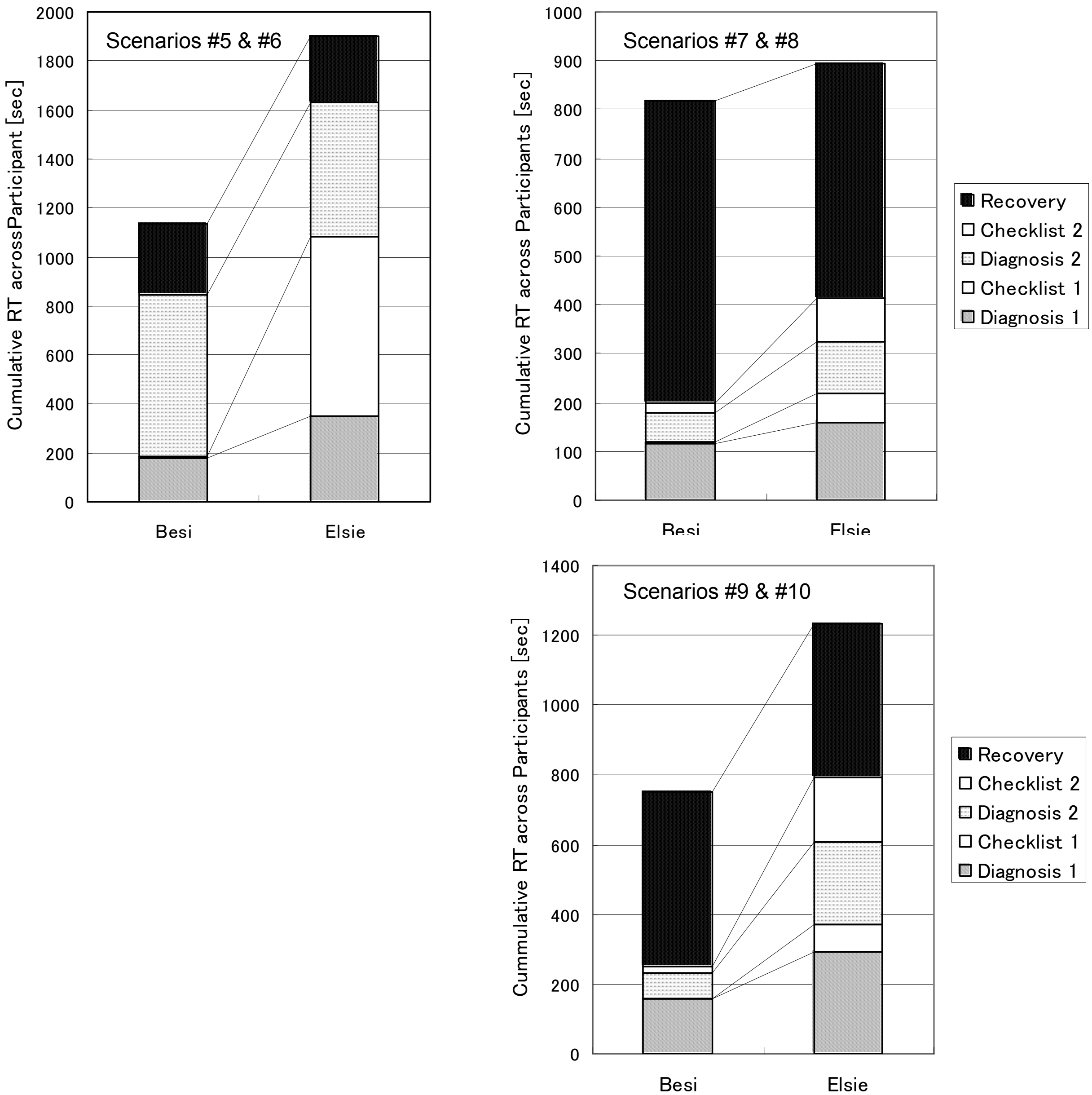

Figure 3.2. Components of Malfunction RT

3.3. PFD Task Results

3.3.1. PFD Task Accuracy

The PFD task was designed in part to assess operator's ability to divide their attention between working a malfunction and monitoring the PFD. Table 3-2 shows the number of individual color changes (PFD task events) that failed to elicit a touch to the upper part of the touch screen. These task "misses" were counted only during the time that an operator was working a malfunction. There are two noteworthy aspects to these results. First, relative to the total number of PFD events, the absolute number of misses was low; participants clearly maintained a high level of attention to the PFD task even while working the malfunctions. Second, however, there was a clear pattern of more misses (across more scenarios) with the Elsie display suite than the Besi suite. These results provide preliminary evidence that attentional tunneling on the malfunction was more severe when the operator had more responsibility for evaluating the off-nominal situation, or, put another way, that the Besi automation enabled operators to divide their attention more efficiently across the two tasks.

Table 3-2. PFD Accuracy Results (On-Task Time Only)

Scenario #	Malfunction(s)	Elsie			Besi		
		# Misses	# Total	% Miss	# Misses	# Total	% Miss
1	A/L1 sw mismatch	0	32	0%	0	25	0%
2	B/L1 sw mismatch (sensor failure)	0	28	0%	0	5	0%
3	1) Load B sw mismatch (restorable), 2) A/L2 sw mismatch (sensor failure)	0	52	0%	2	24	8.3%
4	1) Load A sw mismatch (restorable), 2) B/L2 sw mismatch	0	31	0%	0	25	0%
5	DistAA sw mismatch (restorable)	0	27	0%	0	28	0%
6	DistBB sw mismatch (restorable)	4	56	7.1%	0	20	0%
7	Battery A volts low	0	35	0%	0	26	0%
8	Battery B volts low	0	29	0%	0	20	0%
9	Inverter A failure	1	28	3.6%	0	19	0%
10	Inverter B failure	1	37	2.7%	0	20	0%
11	1) Inverter A failure, 2) Battery A volts low	10	81	12.3%	1	38	2.6%
12	Same as 11	9	106	8.5%	0	62	0%
13	1) Battery A volts low, 2) Battery B volts low	2	54	3.7%	0	58	0%
14	1) Battery B volts low, 2) Battery A volts low	3	65	4.6%	0	49	0%
	Total	30	661	4.5%	3	419	0.7%

3.3.2. PFD Response time

An analysis of the response time on the PFD task revealed that participants responded more slowly to the PFD task when they were working a malfunction (average response time = 2.91 sec for Elsie and 2.76 sec for Besi) compared to when they had completed the procedures and were more free to concentrate their attention on the PFD display (average response time = 2.25 sec for Elsie and 2.12 sec for Besi). The increase in RT while working a malfunction was significant for both Elsie, $t(7)=5.1$, $p < 0.001$ and Besi, $t(7)=3.1$, $p < 0.02$). While no statistical tests comparing Elsie and Besi PFD task RTs were significant, the trend was toward slightly faster responding while handling malfunctions with the Besi display suite compared to the Elsie suite.

3.4. Eye-Movement Data

Operators were asked to perform two tasks 1) monitor the PFD and respond to PFD events and 2) use Elsie/Besi to monitor systems health and resolve malfunctions. The performance data on the PFD task provided strong evidence that PFD monitoring was adversely affected by the requirements associated with fault management, along with some evidence that attention could be more efficiently divided with Besi than with Elsie. We sought further insight into the source of these effects from eye-movement data. For each observer, gaze position was recorded at roughly 60 hz. Each position was classified according to whether the observer was looking at the top half of the display unit (i.e., at the PFD), or at the bottom half of the display unit (Elsie or Besi display). Thus, we determined when operators were attending to the PFD and when they were attending to systems health information or systems-related activities. For the eye-movement analyses, only data from the single-malfunction scenarios (#5 through #10) were included.

Using this simple binary classification of gaze position, we were able to answer several interesting and interrelated questions regarding participants' attentional allocation strategies in the dual task condition. First, what was the impact of being "heads-down" versus "heads-up" on performing the PFD task? Second, how much did participants visually "tunnel" on systems information and malfunction handling activities at the expense of the PFD display? Third, and most provocative, was visually tunneling reduced for Besi compared to Elsie?

The answers to these questions were straightforward. Not surprisingly, participants responded more quickly to the PFD events if, at the time of the color change, they were looking at the PFD display (average RT-PFD=1.94 sec for Elsie and 1.70 sec for Besi) than when they were looking down at the systems display (Elsie RT-PFD=2.99 sec and Besi ==2.86 sec). This "proximity benefit" of approximately 1 sec was significant for both Elsie, t(7)=4.9 $p < 0.002$ and Besi, $t(7)=7.1$ $p < 0.0002$. Next, we calculated the percentage of time observers spent looking at the PFD when they were and weren't working on a malfunction, for both Elsie and Besi. We found when not working a malfunction, operators looked at the PFD frequently for both Elsie (58.7% of the time) and Besi (62.3% of the time). When working a malfunction, the amount of time spent looking at the PFD dropped substantially, to 23.9% for Elsie and 30.5% for Besi. These reductions were significant for both Elsie , $t(7)=8.1$ p < 0.00001 and Besi, $t(7)=6.8$ $p < 0.0002$. Most importantly, during the time they were working malfunctions, the reduction in the time spent looking at the PFD was less for Besi than for Elsie; stated another way, when working a malfunction, participants looked at the PFD significantly more often with Besi (30.5%) than with Elsie (23.9%), $t(7)=3.4$ $p < 0.01$.

3.5. Subjective Measures: Workload

The TLX workload scores and the Bedford workload scores of the paired scenarios (#5-#14) were tested with a Generalized Linear Model (GLM) for the display and scenario-complexity (single vs. multiple malfunction) effects. The main effects included were Participant, Display (Elsie vs. Besi), and Complexity (Single vs. Multi), and interaction effect included was Display x Complexity. The test result indicated that the Participant effect was significant in the TLX scores ($F(7,69) = 14.27$, $p < 0.001$). Furthermore, the results revealed that the TLX scores were significantly lower (less workload) in Besi trials than in Elsie trials ($F(1,69) = 36.40$, $p < 0.001$, TLX mean = 3.77 for Besi, 5.34 for Elsie), and also significantly lower in single-malfunction scenarios ($F(1,69) = 44.57$, $p < 0.001$, TLX mean = 3.80 for single-malfunction, 5.69 for multiple-malfunction). Interestingly, the interaction effect was also turned out significant ($F(1,69) = 9.51$, $p = 0.02$); That means that the reduction of the TLX scores by Besi compared to Elsie was greater in the multiple-malfunction trials than in single-malfunction trials. See Figure 3.3.

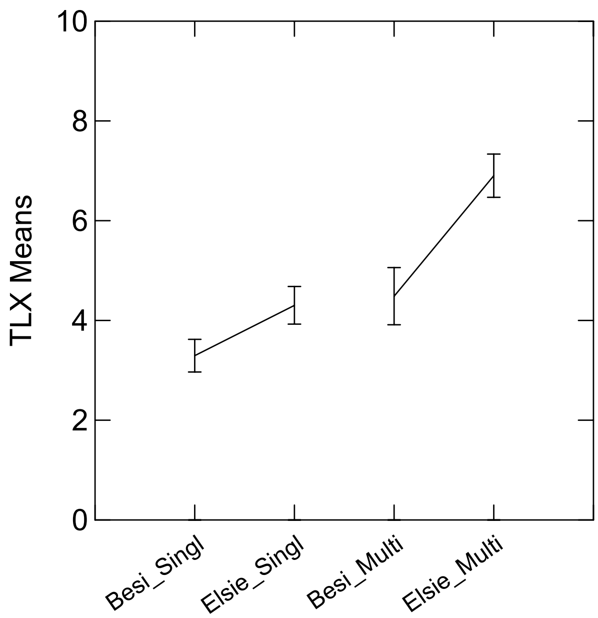

Figure 3.3. Grand Means of TLX Scores by Displays: Single-Malfunction (Left) and Multiple-Malfunction (Right)

The same GLM was also applied to the Bedford workload scores. As in the TLX, the Subject effect was significant in Bedford scores ($F(7,69) = 11.05$, $p < 0.001$). The results also revealed that the Bedford scores were significantly lower (low workload) in Besi trials than in Elsie trials ($F(1,69) = 3.06$, $p = 0.001$, Bedford score mean = 2.75 for Besi, 3.88 for Elsie), and in single-malfunction trials than in the multiple-malfunction trials ($F(1,69) = 30.39$, $p < 0.001$, Bedford score mean = 2.56 for single-malfunction, 4.44 for multiple-malfunction). Unlike the TLX, no significant Display x Complexity interaction effect was found in Bedford scores.

3.6. Subjective Measures: Preference and Usability

After completing all 14 trials, each participant was asked to fill out the display preference questionnaire and indicate their display preference scores on a continuous scale. The left end of the scale was "Absolutely Preferred Elsie," and the right end was "Absolutely Preferred Besi." The mid point was "Neutral." One-sample t-test results showed that the participants preferred Besi significantly more than Elsie for the diagnostic processes ($p < 0.001$, $t(7) = 7.352$), for the recovery processes ($p = 0.003$, $t(7) = 4.466$), and the overall processes as well ($p = 0.002$, $t(7) = 4.687$).

The questionnaire also asked their preference between the Elsie's textual representations of EPS parameters vs. the Besi's graphical representations of EPS parameters. A one-sample t-test result showed that they marginally preferred the Besi's graphical representation over the Elsie's textual representation ($p = 0.058$, $t(7) = 2.269$). The questionnaire also asked their preference between the Elsie's switch panels presented separately from the EPS status information vs. the Besi's switch indicators integrated into the EPS status information. A one-sample t-test result indicated that they significantly preferred the Besi's integrated switch indicators over the Elsie's separate switch panels ($p = 0.054$, $t(7) = 2.312$).

4. Summary of Results

The most important results of our study can be summarized as follows. First, providing the root cause of failures to the participants increased their accuracy of determining the correct root cause and decreased by approximately one half (about 20 seconds) the response time required to make that determination. Second, the root-cause capability of the Besi interface suite contributed to a substantial reduction in rated workload, a reduction that scaled with the overall difficulty and complexity of the off-nominal situation (i.e., the Besi benefit was greater for multiple-malfunction scenarios than for single-malfunction scenarios). Third, we found multiple independent sources of evidence that the Besi interfaces and associated operational concept promoted (or enabled) a more efficient information acquisition and attention allocation strategy between fault detection, isolation, and recovery activities and the monitoring of flight-related displays. We now discuss the implications of these results, our plans for further analyses, and future work.

5. Conclusive Remarks

5.1. Workload Measurement

Rated workload is one of the core metrics being considered for final validation of operational concepts for Constellation Project vehicles. These operations will have to meet requirements that operators rate the workload associated with an operation concept -- using a workload measurement tool such as NASA TLX -- below a predetermined value. Our Elsie condition incorporated the latest concepts for spacecraft electronic user interfaces and display design. Nevertheless, in the Elsie condition, the average workload rating was as high as seven in the most difficult (multi-malfunction) scenarios, which would almost certainly exceed the validation limit. The workload value dropped to below 5 (the half-way point on the scale) in the Besi condition, where the C&W system had root-cause determination capability. While the specific contribution of Besi's automatic root-cause diagnosis and automatic navigation to the appropriate procedure capabilities to the workload reduction (as opposed to the other changes to the Besi/Elsie interface suite) is not known, the results suggest that ECW-style C&W capabilities may be necessary to meet the human factors validation requirements for off-nominal operations concepts for Project Constellation vehicles. Further work will be necessary to verify this hypothesis.

Looking beyond operational concept validation concerns, workload is commonly associated with the amount of spare capacity a crewmember has to deal with additional problems or demands. Currently, the nearly constant contact that crews have with the ground can help alleviate fault management and other sources of operations-related workload through direct ground support. However, once Constellation vehicles leave the vicinity of Low Earth Orbit, ground support for vehicle health management will transition from (virtually) real time, to near-real time, to completely unavailable (depending on vehicle distance and the temporal severity of the malfunction). Constellation vehicles will have to operate in a more autonomous fashion than today's spacecraft. Clearly, a root-cause capability such as the one associated with Besi would give crews more ability to "stay ahead of the vehicle" and work spacecraft operations with less real-time assistance from the ground.

Another point about workload scales is worth mentioning. There has been debate concerning which workload scale is to be used for Operational Concepts validation, NASA TLX or Bedford. The fact that TLX was more sensitive to the manipulation of off-nominal situation difficulty than Bedford is the second example in a spacecraft simulation where TLX has been more sensitive than Bedford (see also McCann et al., 2006). Our recommendation, therefore, is that the program use TLX.

5.2. Future work

While the present sets of results are intriguing, many more analyses remain. Our eye-movement recording apparatus actually had a spatial resolution of approximately ½ inch, allowing for much more fine-grained analyses of display usage, information acquisition strategies, and the like, than was possible by simply dividing the display real estate into "upper" and "lower" regions. For example, these more focused analyses will be employed to ascertain the temporal distribution and frequency with which participants shifted their gaze from the fault management displays to the PFD and back again. In turn, these data will enable us to make a more precise understanding of the exact source of the divided attention benefit for Besi, and incorporate that understanding into an improved interface design that promotes even more divided attention capability.

One thing is clear. Off-nominal situation management is a resource-intensive activity that consumes much of an operator's attention until it is completed. In other words, vehicle operators don't have a great deal of spare capacity to work more than one malfunction at a time. When overlap between two independent faults occurs, management of the two problems tends to be quite serial, and performance on both degrades (McCann et al,, 2006). That being the case, the best approach to enhancing crewmembers' vehicle management capabilities is to carefully automate selected aspects of the fault management process so that the total fault management time is reduced, as long as that reduction is accomplished with no loss of situation awareness and no reduction in accuracy. Quite simply, the more rapidly a fault management operation is completed, the less chance there is that a second malfunction will occur before the current problem is resolved.

That being said, there are indications from the current results that a carefully designed fault management system can enable more multi-tasking capabilities, which will be of great interest to Project Constellation managers who are worried about requirements that Constellation vehicles can be operated by a single crewmember. In the coming year, we will be attempting to enhance operators' multi-tasking capabilities by making greater use of multi-modal interfaces with onboard automation.

5.3. Cognitive Modeling

Concurrent with the empirical work summarized in this report, the DRP has been supporting a human performance modeling development effort here at NASA Ames. The goal of this work is to develop a tool that can be used to predict operator performance for a specified operations concept and the associated user interfaces. Such a tool could be of great value in streamlining display design prototyping and testing operational concepts without the need for resource-intensive and time-consuming human-in-the-loop simulations. In addition, a validated human performance model could be a very valuable addition to the development of an advanced interactive training environment in which real-time metrics of trainee performance (such as scan patterns) would be evaluated online, and compared to models of optimal, or highly trained, performance. The trainee's performance could then be shaped to more closely emulate that of the expert model. A key to our modeling development effort is to decompose cockpit tasks into their smallest meaningful "units of behavior," which we derive from analyses of participant eye movements in the ISIS simulator.

5.4. Programmatic Observation

The user interfaces and operations concept for Constellation Project vehicles are just now attaining enough definition to support human-in-the-loop test and evaluation. The hardware and software infrastructure necessary to support human-in-the-loop simulation of vehicle operational concepts is both labor intensive and resource intensive. Our facility combines that infrastructure with a suite of human performance assessment and modeling capabilities unmatched in the agency. With DRP support, we look forward to further development of these capabilities and tools in FY 08 and beyond.

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Appendix

Participant Training Manuals
Volumes 1 & 2

Evaluation Study for Crew Exploration Vehicle (CEV) Advanced Caution and Warning System

Participant Training Manual

Volume 1 of 2

Intelligent Spacecraft Interface Systems (ISIS) Lab &
Advanced Diagnostics and Prognostics Testbed (ADAPT) Lab
NASA Ames Research Center

August 2007

Table of Contents
Volume 1

1 Introduction

1.1 Background

Although they are both flight vehicles, operating a spacecraft differs from operating an aircraft in fundamental ways. For example, compared to aircraft systems, spacecraft systems are more complex and dynamic, are less mature, and have to operate in much harsher and more rapidly changing physical environments. For instance, during the ascent phase, a spacecraft experiences fast changes of g-force levels (1G to 5G to micro gravity), high cockpit vibration levels, temperature levels (surface temperature to extremely high temperature to absolute 0K), atmospheric pressure levels (surface atmosphere to vacuum) all within a mere 10 minutes. These factors combine to make spacecraft systems considerably more likely to experience mechanical malfunctions than their counterparts on aircraft, and the impacts of those failures are more likely to pose an immediate threat to the safety of the mission and the crew. Thus, a spacecraft operator must be capable of functioning as a traditional flight engineer able to diagnose and respond to systems malfunctions in a timely and accurate fashion. Spacecraft designers must therefore pay particular attention to the vehicle caution and warning and fault management interfaces, which provide the crew with the means to monitor systems status, orient quickly to the presence of an anomalous situation, and handle the problem.

1.2 Purpose of the Study

NASA is designing a new generation of spacecraft, the Crew Exploration Vehicle (CEV) *Orion*, which will provide crew transportation to and from the International Space Station in Low Earth Orbit, the Moon, and beyond. The purpose of the study is to evaluate different design concepts for the Orion's Advanced Caution and Warning System (ACAWS) that will help crewmembers identify, diagnose, and recover from vehicle systems malfunctions. The human-in-the-loop simulation results also will provide valuable information for development of operator performance model.

1.3 Participant Selection Criteria

We are looking for participants who meet <u>all</u> of the following requirements:

1. Instrument rated pilots
2. NOT wearing hard contact lenses (for eye-tracking reason)
3. Available for four half-day sessions during weekdays
4. US citizen

1.4 Time Requirements and Agenda

Prior to training	Read and study training materials (vol. 1) at home (1 hours)
2~7 days prior to data collection	Two half-day training sessions (4 hour each), which can occur on either a single day or two separate days.
Prior to data collection	Read and study training materials (vol. 1 and 2) at home (3 hours)
August - September	Two half-day data-collection sessions (4 hours each) on two separate days.

1.5 What Should You Expect?

The Orion cockpit will be operated by two operators, one sitting in the left seat, and one in the right seat. However, one of the requirements for this vehicle is that one crewmember must be able to operate it in case the other crewmember is incapacitated. In this study, we will ask you to play the role of a single CEV operator during the short ascent stage of your mission, which lasts from launch to Earth orbit insertion (approximately 10 min.). Before you assume that role, you will receive thorough training and familiarization on the two interconnected CEV subsystems that you will be responsible for monitoring and managing: The Electrical Power System (EPS) and certain elements of the Environmental Control and Life Support System (ECLSS). By learning the information in this document and participating in the two half-day training sessions, you will learn the EPS-ECLSS functional connections, how to recognize and diagnose system malfunctions (e.g., pump failures, relay failures, battery failures), and the associated recovery procedures provided on the electronic checklists. You will be trained to perform these fault detection, isolation, and recovery tasks using two different ACAWS interfaces, that we call “Elsie” and “Besi” in this experiment. To make the workload and task environments as realistic as possible, we will also ask you to monitor and report CEV vehicle and flight parameters on a CEV Primary Flight Display (PFD) in addition to the EPS-ECLSS tasks. Flying a spacecraft is a multi-task operation, just like flying an aircraft!

Before beginning the data collection, we will ask you some review questions, which cover the basics you learned in the two training sessions. If you answer any questions incorrectly, we will brief you until you understand them. This review session is critical for us to ensure that all participants in the study attain the same level of understanding of the interfaces and the tasks. In fact, it is so important that, if we feel that you are not at the level of participating in this experiment, we might have to ask you to withdraw. All information you will be asked in the review session are covered in this training manual. So, please take time to read it carefully before the training sessions, and review it again afterward. This will significantly increase your odds of passing the review session with flying colors!

Once you pass the review session, we will start the first of the two data-collection sessions on the same day. Then, you will be scheduled for the second half-day data-collection session within a week from the first one. Each half-day session will consist of seven ten-minute ascent-phase trials. During each trial, we will collect objective measures of your performance, such as the accuracy with which you complete malfunction procedures, your information scanning behaviors as revealed by your eye movements (i.e., what you look at, and for how long), and subjective measures such as situation awareness level, workload, and display preferences. These data will provide us valuable information in evaluating the two ACAWS display concepts.

Your performance will also be video-recorded. Please rest assured that these video clips will be used solely for research purpose, and will never be released in a manner that reveals your identity (please read "Your Rights" section below). During the runs, you will wear a baseball cap that houses an infra-red video head-and-eye-tracker system. If you experience any discomfort (e.g. the baseball cap is too tight, or your eyes become uncomfortably dry), please tell us so, so that we can give you longer breaks, or even end the experiment (again, please read "Your Rights" section below).

1.6 Your Rights

At any point of the study, you have the right to withdraw from the study for any reason without any penalty. Likewise, we (the experimenters) also reserve the right to request you to withdraw from the study at any point of the study for any reason.

In any case, we greatly appreciate your participation, and will compensate you for your time. This remains true even if you (or we) decided to stop the experiment in the middle, resulting in an incomplete data set. The time includes four hours for at-home reading of this training manual, two four-hour training sessions, and two four-hour data-collection sessions. That is 20 hours in total. If you do not pass the review session before the data collection, you will still be compensated for the time up to the review session. The rate is $25.75/hour. We will also compensate for your commute up to 50 miles each way. The rate for commuting compensation is $0.485/mile.

All the data we collected in this study will be used only for research purpose. The data may be used in our publications, but will never be released in a way that the data can be associated with you, unless approved by a written waiver from you.

The ARC 475, Human Research Minimal Risk Consent form is included in this training manual packet for your review. Please read it carefully. If you consent to all the items on the form, please sign it and give it to the experimenter before the data collection starts. If you have any questions, please do not hesitate to contact Miwa Hayashi (mhayashi@mail.arc.nasa.gov, 650-604-1397) or Rob McCann (Robert.S.McCann@nasa.gov, 650-604-0052).

2 Crew Exploration Vehicle (CEV)

2.1 Overview

Let us start with an overview of the CEV Orion and its ascent operations before getting into the details of its ECLSS and EPS, so that you will have better understanding of the operational context of the simulation.

Crews will start their mission strapped into their seats inside the CEV, a tapered Apollo-capsule-like spacecraft resting on top of a the Crew Launch Vehicle (CLV). The CLV is a propulsion "stack" encompassing two stages (Figure 2-1). The CLV's first stage will consist of a single, five-segment (i.e., elongated) version of the same solid rocket booster that helps propel the shuttles into orbit today. On top of this solid rocket booster is the second, upper stage, which consists of a single evolved version of the engines used on the Saturn V in the Apollo program. Above the CLV, the CEV consists of three components, the Crew Module (CM), the Service Module (SM) and the Launch Abort System (LAS). The SM is directly above the CLV's second stage and houses a smaller rocket engine. Directly above the SM is the Crew Module (CM). Finally, the slim cylindrical rocket on the top end of the CM is the Launch Abort System (LAS), which separates the CM from the stack in case of critical failure.

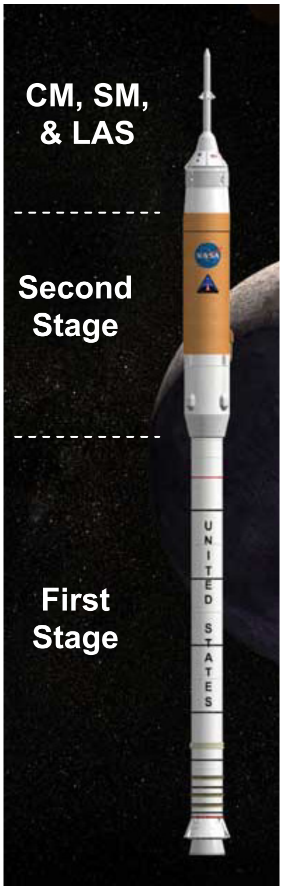

Figure 2-1. CEV on top of the Crew Launch Vehicle

Figure 2-2. CEV Launch

2.2 The Ascent Stage

The ascent stage begins at launch (Figure 2-2) and ends at orbit insertion – the point at which the CEV reaches its targeted velocity (25,000 ft/sec or Mach 22.4) and position (altitude and location with respect to the Earth's surface) which ensures that, once the propulsion systems have shut down, the vehicle has achieved the targeted orbit. You will be monitoring this on your Primary Flight Display (PFD). Details of the PFD will be explained later. In this section, we will walk you through major events that unfold over the course of the ascent flight phase.

Following liftoff, the first important event is the transition from the first stage, during which the solid rocket booster is providing thrust, to the second stage, during which the upper stage engine is providing thrust. You will observe this stage transition on the PFD as a sudden drop in G level and a transition of the thrust indication from the first-stage thrust icon to second-stage thrust icon.

Another crucial event to monitor is the transition of your abort options. Aborts – the termination of the nominal mission profile due to a catastrophic failure that requires immediate vehicle return – will be always a critical focus of training for CEV crews. While we won't actually cause an abort in this experiment, it is crucial even on nominal flights to maintain awareness of the different abort options ("abort modes") that become available over the course of the ascent phase. After liftoff, the LAS is capable of separating the CM from all the components below it in the stack, and propelling it out to sea for a water landing. That kind of abort, where the LAS fires and blasts the CM from the rest of the stack, is a *Mode 1* abort. Later, after the solid rocket booster separates and the upper (second) stage engine ignites, the LAS is jettisoned from the vehicle (Figure 2-3). Now, if something goes wrong with the second stage engine, the option is to fire the SM engine and separate the CM/SM from the upper stage. Depending on a number of factors, such as the altitude and velocity of the vehicle at the time of separation, the CM may travel across the Atlantic and land in Africa or Europe, or it may orbit the Earth once and land off Baja California. Collectively, we refer to this as a *Mode 2* abort.

You will monitor these two abort modes (1 and 2) via a box on the PFD which indicates Mode 1 during the early part of the flight, and then transitions to say Mode 2 after the LAS is jettisoned.

After the orbit insertion, the second stage is jettisoned. Then, the CEV uses the SM's propulsion for thrust. (Figure 2-4)

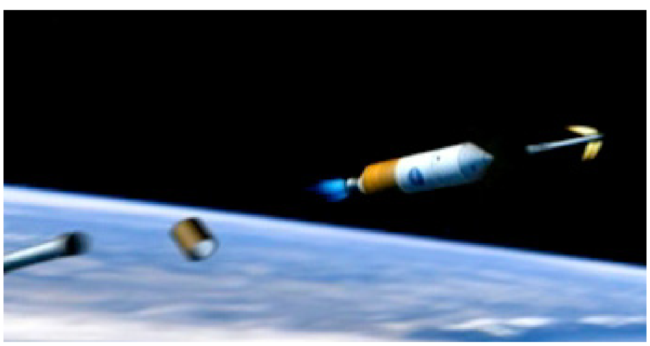

Figure 2-3. LAS jettison following solid rocket booster separation

Figure 2-4. CEV approaching to the International Space Station

3 Environmental Control & Life Support System (ECLSS)

3.1 System Overview

In our simulation, the Electrical Power System (EPS) supplies electrical power to various powered devices (e.g., fans, pumps, valves, etc.; hereafter referred to as “loads”) representative of the loads likely to be found in the CEV’s Environmental Control and Life Support System (ECLSS)*. The ECLSS maintains the spacecraft’s thermal stability and provides a pressurized, habitable environment for the crewmember (you), and therefore, is one of the most important systems affecting crew safety in a manned spacecraft. The ECLSS also maintains the cool air temperature for the onboard avionics, another important CEV capability that you would not like to lose. In our simulation environment, the dynamic characteristics of these ECLSS loads are computer simulated.

The ECLSS maintains an appropriate temperature in various areas of the spacecraft via fans located in strategic locations and two loops that circulate water and Freon throughout the vehicle. Each of these components is instrumented with temperature, pressure, and flow sensors to relay operational status to the crew. There are also sensors to measure parameters important to the habitable portion of the vehicle, such as cabin pressure.

3.2 ECLSS Display

In this evaluation, part of your task is to monitor those ECLSS parameters that provide insight into those ECLSS loads that are included in our EPS-ECLSS model. You can monitor the information about ECLSS supported by our simulation via the ECLSS system summary display (Figure 3-1). The formats of the ECLSS display are the same regardless the types of the ACAWS display (i.e., Elsie or Besi) you are using.

As Figure 3-1 shows, the ECLSS display contains many parameters. However, the critical ones that you actually need to pay close attention to are the ones highlighted with bold font, also marked with magenta triangles in Figure 3-1. Non-critical parameters are also marked with amber triangles. Those marked with triangles in Figure 3-1 are *supported* in our simulation. That is, they are simulated in our EPS-ECLSS model, and thus, may show off-nominal values as a response to an ECLSS-load or EPS-component failure. All other unmarked parameters are *non-supported* in this simulation, and will stay near their nominal values.

Off-nominal values supported prameters are shown by a font color change – red if it is a critical parameter, and yellow if it is a non-critical parameter – and a co-located arrow to represent a value that is too high (up arrow) or too low (down arrow). You will also receive a corresponding ECLSS Caution & Warning (C&W) message on the ACAWS display, so you will know if anything becomes off-nominal in the ECLSS, even when you are not watching the ECLSS display. More explanations about the C&W system and associated fault messages are in the ACAWS Display sections (in Volume 2).

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* Since we don’t yet have a design for the Orion ECLSS, wherever possible we’ve mapped these loads onto equivalent components of the existing ECLSS system onboard the Space Shuttles.

Figure 3-1. ECLSS Display

Having any red numbers in the ECLSS display means that some of the critical ECLSS loads are not functioning correctly (if they are not sensor failures), which could shortly lead to a life-threatening condition. Yellow numbers indicate malfunctions of non-critical ECLSS components, which the crew can survive without if necessary. Sometimes, you may need to sacrifice these non-critical ECLSS components in order to save the critical ones. Note that these off-nominal values could be caused by any of 1) a failure of the ECLSS load itself, 2) a failure of an upstream EPS component, or 3) a sensor failure (false alarm).

The ECLSS display is divided into five main areas: Smoke, Atmosphere, Fans, Water Loop, and Freon Loop.

1) Smoke
The Smoke area presents information about the level of smoke detected. All parameters in this area are non-supported in this experiment, and the values stay near their nominal values (0.0).

2) Atmosphere
The Atmosphere area presents information about the air in the crew cabin. The Pressure Control System (PCS) maintains the cabin pressure (*Cabin P*) at approximately 14.7 psi (showing “15” in Figure 3-2), as well as the percent of oxygen (*%O2*) and the partial pressure of oxygen (*ppO2*) in the cabin at the appropriate level. *Cabin P* is the only critical parameter in the Atmosphere area, and is shown in bold font. The *%O2*, *ppO2*, PCS flows and reserve quantity for oxygen and

nitrogen (*PCS O2 Flow*, *PCS N2 Flow*, and *PCS N2 Qty*) are all non-supported, and will stay near their nominal values.

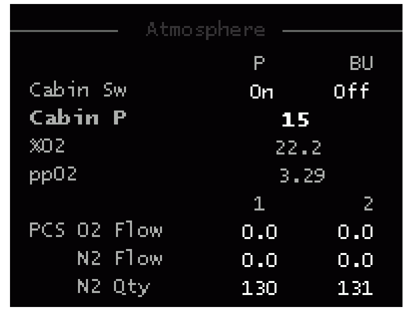


Figure 3-2. Atmosphere Area

The *Cabin P* is a sensitive indicator of the health and status of the PCS. There are actually two identical PCSs, a primary (*P*) and a backup (*BU*). If the primary PCS is on (i.e., *Cabin Sw P* is On), the value of *Cabin P* is an output of the primary PCS sensor; if the backup PCS is on (i..e, *Cabin Sw BU* is On), the *Cabin P* value is an output of the backup PCS's sensor.

Your task is to monitor that at least one of the *Cabin Sw* (P or BU) is On, and that the critical parameter, *Cabin P*, remains close to 14.70. If *Cabin P* exceeds pre-determined limits, the value will turn red and a red arrow will appear next to it. You will also receive an ECLSS C&W message, "Cabin P Low (or High)" in the ACAWS display's C&W message area. You must then diagnose the root cause of this problem and follow the appropriate checklist procedure to fix it.

3) Fans

The Fans area presents the status information regarding the fans used to keep the cabin and avionics-bay temperatures cool.

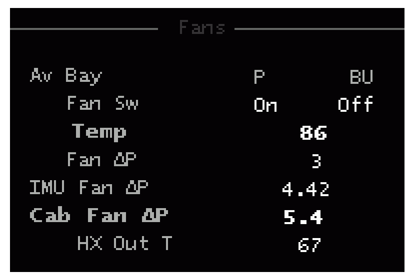


Figure 3-3. Fans Area

The Fans area contains two critical parameters – avionics bay temperature (*Av Bay Temp*) and cabin fan pressure change (*Cab Fan ΔP*). Both are shown in bold font. The Av Bay Temp is the sensed parameter you should use to check the status of the avionics bay fan, and the *Cab Fan ΔP* is the sensed parameter you should use to check the status of the cabin fan. There are actually two avionics bay fans and two cabin fans, one designated primary (*P*) and one designated backup (*BU*). Note that the Fans Area displays the switch configuration for only the avionics bay fan (*Av Bay Temp*). For instance, in Figure 3-3, you can tell the primary avionics bay fan is being used (*Av Bay Fan Sw P* is on), but there is no indication about which fan (P or BU) is being used for the cabin fan (*Cab Fan ΔP*).

Actually, the *Av Bay Temp* value has a positive correlation with the *Evap Out T1, T2, T3* parameters in the Freon Loop area, since, if the Freon Loop is overheating, the Freon flowing through the avionics bay will be too hot, and the avionics bay temperature will increase. Thus, crosschecking the *Evap Out T* parameters with *Av Bay Temp* is an effective way to see if an off-nominal *Av Bay Temp* reading is a sensor failure or an actual failure.

Your task is to monitor that at least one (*P* or *BU*) of the avionics bay fan switches (*Av Bay Fan Sw*) is On, and that the two critical parameters stay within normal operational limits (i.e., stay white). When the *Av Bay Temp* or the *Cab Fan ΔP* shows an off-nominal value, the corresponding value turns red, and an arrow shows up next to it. Also, an ECLSS C&W message, "Av Bay Temp High (or Low)" or "Cab Fan ΔP Low (or High)," respectively, will be issued in the C&W message area of the ACAWS display. You must then diagnose the root cause of this problem and follow the appropriate checklist procedure to fix it.

Supported non-critical parameters in this area are avionics bay fan pressure change (*Av Bay Fan ΔP*) and cabin heat exchanger (HX) output temperature (*Cab HX Out T*). Inertial Measurement Unit fan pressure change (*IMU Fan ΔP*) is non-supported, and will stay near its nominal value.

4) Water Loop

The Water Loop area presents the status information about the water coolant loop, which removes heat from the cabin air via an air/water heat exchanger and transfers the heat to the Freon coolant loop. The water loop helps maintain cabin air temperature within an acceptable range.

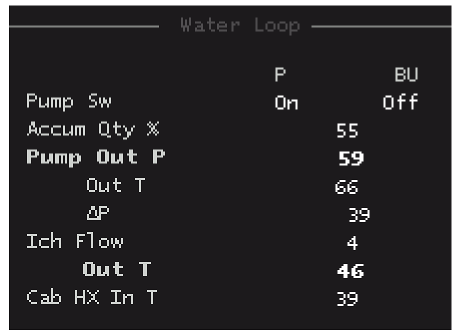


Figure 3-4. Water Loop Area

The two critical parameters in this area are pump output pressure (*Pump Out P*) and interchanger output temperature (*Ich Out T*). Both are shown in bold font. The *Pump Out P* is the parameter you should check to get the status of the water-loop pump, and the Ich Out T is the parameter associated with the status of a water-loop bypass valve, electrically actuated to the "open" position, which controls the flow amount and temperature of the water. There is a primary (P) and a backup (BU) water-loop pump and bypass valve, and can be switched between the *P* and *BU* independently from each other. However, the Water Loop Area shows the switch configuration of only the *Pump Out P*. For instance, Figure 3-4 shows that the *Pump Out P* value is the output associated with the primary water pump (i.e., *Pump Sw P* is On), but there is no indication about which bypass valve (P or BU) is being used.

Monitor that at least one of the pump switches (*Pump Sw*) is On at all times, and that the two critical parameters stay nominal (i.e., stay white). When they go out of limits, the values turn to red and arrows appear next to them. Also, corresponding ECLSS C&W messages, "Pump Out P Low (or High)" and "Inc Out T Low (or High)," respectively, appear in the C&W message area of the ACAWS display. You must then diagnose the root cause of this problem and follow the appropriate checklist procedure to fix it.

Supported non-critical parameters in the Water-Loop area are interchange flow (*Ich Flow*) and cabin heat exchanger (HX) inlet temperature (*Cab HX In T*). The other parameters, accumulator quantity (*Accum Qty %*), pump output temperature (*Pump Out T*), and pump output change in pressure (*Pump Out ΔP*) are non-supported, and their values stay near the their nominal values.

5) Freon Loop

The Freon Loop area presents the information regarding the Freon coolant loop system, which collects heat from the water loop and other onboard systems, such as the avionics equipment in the avionics bay, and removes the heat accumulated in the Freon into the atmosphere or space via a flash evaporator system (FES).

There are three critical parameters in this area – FES output temperature readings, T1, T2, and T3 (*Evap Out T1*, *T2*, and *T3*), that come from three redundant sensors. All three are shown in bold font. The three *Evap Out T*s all measure the temperature of the Freon as it exits the FES. Thus, the *Evap Out T*s are sensitive indicators of the health of the Freon-loop. It probably won't surprise you to learn that there are actually two identical Freon-loops, a primary (*P*) and a backup (*BU*). If the primary Freon loop is on (i.e., *Pump Sw P* is On), the *Evap Out T*s indicate the outputs from the primary Freon-loop sensors; if the backup system is on (i.e., *Pump Sw BU* is On), then the *Evap Out T*s are the outputs from the backup Freon-loop sensors.

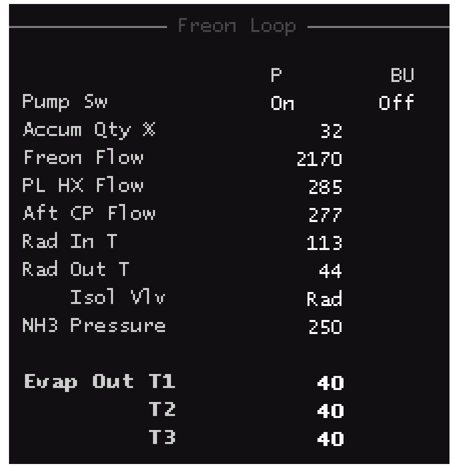


Figure 3-5. Freon Loop Area

Again, your task is to monitor that at least one of the pump switches (*Pump Sw*) is On, and that the three critical parameters (*Evap Out T1*, *T2*, and *T3)* stay within limits (i.e., stay white). When they go out of limits, the values turn red and arrows appear next to them. In the ACAWS display, you will also receive ECLSS C&W messages, "Evap Out T# High" (# = 1, 2, or 3), in the C&W message area. The *Evap Out T*s are redundant sensors, so, if any of the *Evap Out T* parameters goes off-nominal, check against the other *Evap Out T*s. Check also for corroboration with the *Av Bay Temp* sensor in the Fans area. If this is an actual failure, the *Av Bay Temp* should be showing off-nominal values as well as the other two *Evap Out T*s. Otherwise, this is likely a sensor failure.

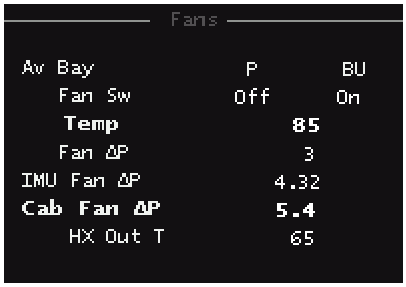
All other parameters in the Freon Loop, accumulator quantity (*Accum Qty %*), Freon flow rate (*Freon Flow*), payload heat exchanger flow rate (*PL HX Flow*), avionics bays aft cold plates flow (*Aft CP Flow*), radiator inlet and output temperatures (*Rad In T*, and *Rad Out T*, respectively), the setting of the radiator isolation valve (*Rad Isol Vlv*), and ammonia pressure (*NH3 Pressure*), are non-supported, and their values will stay near their nominal values.

3.3 Self-Check Quiz - ECLSS

1. All parameters on the ECLSS display are driven by our EPS-ECLSS model in this simulation. (true / false)
2. The ECLSS display is the only place you can monitor the status information of the ECLSS loads.(true / false)
3. Presence of any red indication on the ECLSS display means that you will likely face a life-threatening condition shortly (except a case of sensor failure). (true / false)
4. Values of the critical parameters turn to yellow when they are just slightly away from the nominal value. (true / false)
5. How many Evap Out T sensor(s) are redundantly measuring a single Freon loop temperature? _______
6. Cabin P value and Evap Out T values have a positive correlation with each other. (true / false)

7. An off-nominal value (shown in either red or yellow) could be caused by a sensor failure. (true / false)

8. (See figure) In this example, avionics bay fan is powered by the backup system, but which system is powering the cabin fan is not shown. (true / false)



9. The ECLSS display formats are exactly identical between the two ACAWS displays. (true / false)

4 Electrical Power System (EPS)

4.1 System Overview

The EPS provides AC and DC power to the ECLSS loads. (In this experiment, both the EPS and the ECLSS are computer simulated.) In this section, we will first introduce the structure of the EPS, and then relate it to the ECLSS loads described in the previous section. Then, the basic operations of the EPS will be covered.

The EPS is a battery-based system, and divided into four sections: Generation, Storage, Distribution, and Loads.

The Generation section contains all components necessary to generate electrical power needed to charge the batteries. The EPS can be charged by either photovoltaic (PV) panels (i.e., solar panels) or ground-based electric power sources. In the actual CEV operations, the batteries will be fully charged prior to ascent from ground-based power sources, and the vehicle will have to rely on battery power during the ascent. After reaching orbit, the PV panels will be deployed and used to recharge the batteries. Similarly, in our simulation, the batteries will start each ascent fully charged. You cannot re-charge them during the ascent. If one of the batteries fails, the EPS must be reconfigured to use a backup battery to replace the failed battery. The Generation section also contains three charge controllers that regulate the charging process so the downstream batteries do not get overcharged.

The Storage section contains three 24v DC batteries (Battery A, Battery B, and Battery C). Its task is to store the electrical power generated in the previous section. The Storage section contains a set of circuit breakers and switches that can be used to connect any of the charge controllers to any of the batteries.

The Distribution section distributes the power stored in the batteries to the ECLSS loads. It contains circuit breakers and switches, which can be configured to connect any of the batteries (A,B, and C) to either of the two load banks (Load Bank A and Load Bank B). It also contains two power inverters (Inverter A and Inverter B), which convert DC power from the batteries to the AC power required by some of the ECLSS loads.

Finally, the Loads section contains switches to turn the power to individual ECLSS loads on or off. Each load bank contains six AC loads (L1 through L6) and one DC load (L7 on Load Bank A, L8 on Load Bank B). Of the six AC loads on each load bank, the first two loads (L1 and L2) are critical loads that must always be powered, the second two loads (L3 and L4) are non-critical loads that the crew could survive without if power is lost temporarily, and the last two loads (L5 and L6) are backup loads to the two critical loads (L1 and L2) on the other load bank. The backup loads (L5 and L6) are duplicates of the primary critical loads and should be turned on only when the primary loads have failed. Of the two DC loads, the one on the Load Bank A (L7) is a primary critical load, and the other one on Load Bank B (L8) is a backup for L7. L8 is normally off unless L7 has failed. All the primary loads, L1 to L4 on both load banks and L7 on Load Bank A, will be called “nominal loads.”

4.2 EPS Components

Figure 4-1 illustrates a standard initial configuration for the power distribution from the batteries to the loads. Actually, this configuration is the only initial configuration that you will ever see in this experiment; so, we will drop "standard" from it and call it simply the initial configuration hereafter. Now, in the initial configuration, Battery A is powering Load Bank A, and Battery B is powering Load Bank B. Battery C is a fully functional backup. If Battery A or Battery B fails, either Load Bank A or Load Bank B will be suddenly unpowered. You will have to complete the procedures to connect the affected load bank to Battery C, thereby restoring power.

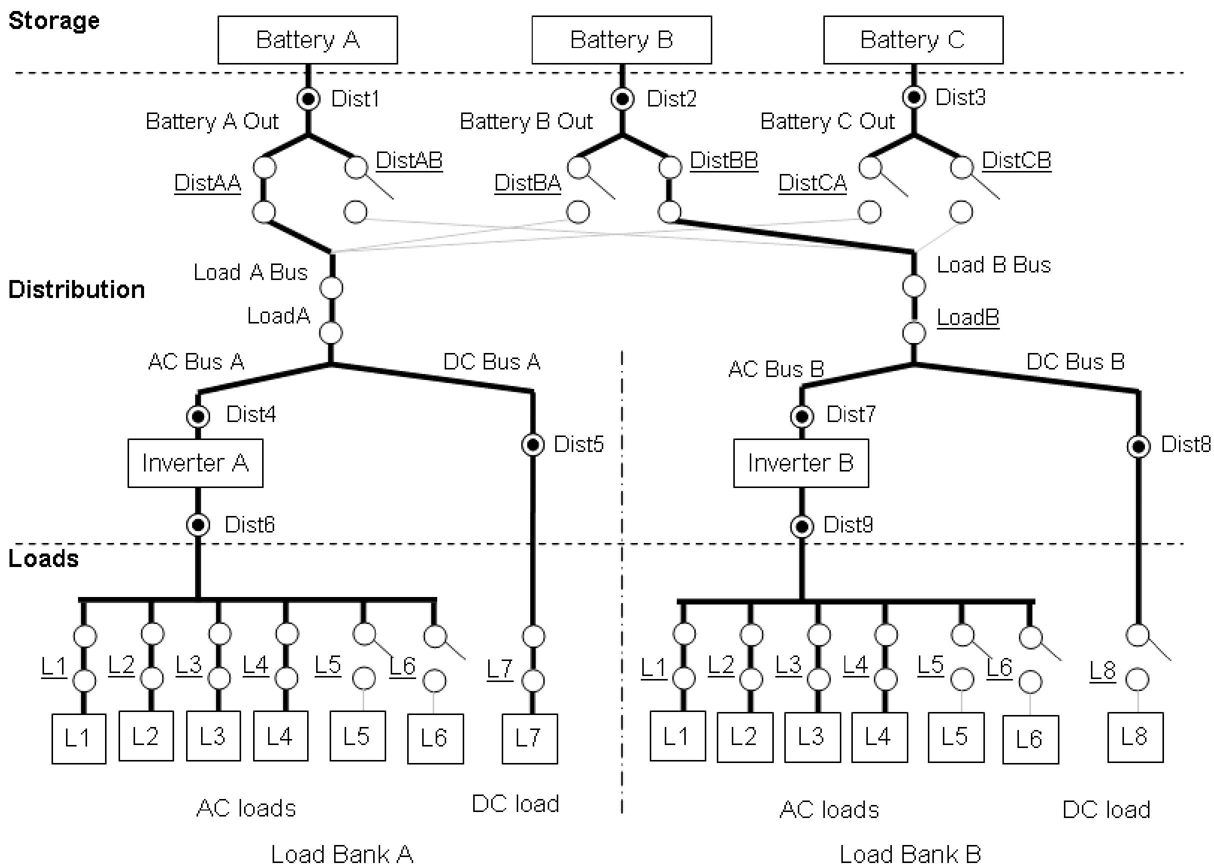


Figure 4-1. EPS Standard Initial Configuration

In Figure 4-1, the switches (often shorthanded as "sw") with underlined labels are under user control and you can turn them on (closed) or off (open) to control the electrical power flow. DistAA sw connects Battery A to Load A Bus, DistAB sw connects Battery A to Load B Bus, and so on. In the initial configuration, only DistAA and DistBB are on, and all other DistXY switches are off. The LoadA sw connects the Load A Bus to both the AC Bus A and the DC Bus A. Similarly, the LoadB sw connects the Load B Bus to the AC Bus B and the DC Bus B. Both LoadA and LoadB switches are on in the initial configuration. Finally, the load switches, L1 through L8, control the power to the individual loads. In the initial configuration, only the nominal-load switches (i.e., all except backup-load switches) are on.

Double circles (Dist1 to Dist9) are the circuit breakers (often shorthanded as "cb"). The circuit breakers protect the circuit by tripping themselves when current gets higher than the pre-determined level. In the initial configuration, all circuit breakers are on (i.e., not tripped). Inverter A is located between Dist4 and Dist6 cbs, and Inverter B is located Dist7 and Dist9 cbs. Inverters convert DC power to AC power for the AC loads. In addition, when they detect insufficient voltage, the inverters automatically shut off to protect the batteries. Note that you will NOT have access to the controls of any circuit breakers or either inverter. Thus, if a circuit breaker trips or an inverter shuts off, you will have to reconfigure the EPS to restore the lost ECLSS functions.

4.3 Relationship to ECLSS Loads

How do the EPS loads, L1, …, L8, relate to the the powered ECLSS components mentioned in the previous section? You can monitor the health of the individual loads (L1, L2, …) via the ECLSS display (Figure 3-1). Table 4-1 lists the mapping between the EPS loads and the ECLSS parameters and associated equipment. The table also shows the loads' wattage, whether it is a nominal load or not, and whether it is a critical load or not (critical loads are shown in bold font in the ECLSS display). The ECLSS parameters not listed in Table 4-1 are *non-supported* in this simulation, and these values stay near their nominal values.

Table 4-1. Mapping between EPS Loads and ECLSS

Load Bank A	ECLSS Parameter	ECLSS Display Area	ECLSS Equipment	Watt	Nominal Loads	Critical Loads*
L1	Evap Out T1, T2, T3, Av Bay Temp	Freon Loop, Fans	P Freon Loop	75	√	√
L2	Cab Fan ΔP	Fans	P Cabin Fan	120	√	√
L3	Av Fan ΔP	Fans	Av Bay Fan	30	√	
L4	Cab HX Out T	Fans	Cabin Temp Valve	60	√	
L5	Pump Out P BU	Water Loop	BU Water Loop Pump	35		(√)
L6	Ich Out T BU	Water Loop	BU Water Loop Bypass Valve	55		(√)
L7	Cabin P	Atmosphere	P PCS	10	√	√
Load Bank B	**ECLSS Parameter**	**ECLSS Display Area**	**ECLSS Equipment**	**Watt**	**Nominal Loads**	**Critical Loads***
L1	Pump Out P	Water Loop	P Water Loop Pump	35	√	√
L2	Ich Out T	Water Loop	P Water Loop Bypass Valve	60	√	√
L3	Ich Flow	Water Loop	Water Loop Ich Valve	30	√	
L4	Cab HX In T	Water Loop	Sensor Bank	60	√	
L5	Evap Out T1, T2, T3 BU, Av Temp BU	Freon Loop, Fans	BU Freon Loop	75		(√)
L6	Cab Fan ΔP BU	Fans	BU Cabin Fan	120		(√)
L8	Cabin P BU	Atmosphere	BU PCS	10		(√)

* : (√) indicates a backup critical load

Generally, Load Bank A provides power to the ELCSS loads in the Fans, the Freon Loop, and the Atmosphere areas, whereas the Load Bank B provides power to the ECLSS loads in the Water Loop area. The alternate load bus powers backup loads for all critical loads. That is, Load Bank A powers critical loads in the Fans, Freon Loop, and Atmosphere areas, while Load Bank B powers critical loads in the Water Loop. More specifically, the loads, L5 and L6 on the Load Bank A, are the backup of L1 and L2 on the Load Bank B, respectively. Likewise, L5 and L6 on the Load Bank B, are the backup of L1 and L2 on the Load Bank A, respectively.

4.4 Load Shedding

The batteries do not have the capability to provide power to all six loads on a single load bus at the same time for the entire duration of the ascent phase (i.e., before the solar panels can be extended). Thus, an important consideration when turning on a backup load is to confirm that the battery will have adequate capacity. The **maximum power capacity** constraint to satisfy this requirement is **300W per load bank**. Before turning on a backup load, the crew must determine which non-critical loads must be turned off ("shed") to remain below this amount. Since Load Bank B contains less total wattage of the nominal loads than Load Bank A, Load Bank B requires slightly less load-shedding requirement than Load Bank A. The following rules detail this requirement (See Figure 4-2):

- On Load Bank A,
  - If either backup load (L5 or L6) is turned on, both non-critical loads (L3 & L4) must be turned off. (Figure 4-2 (b))

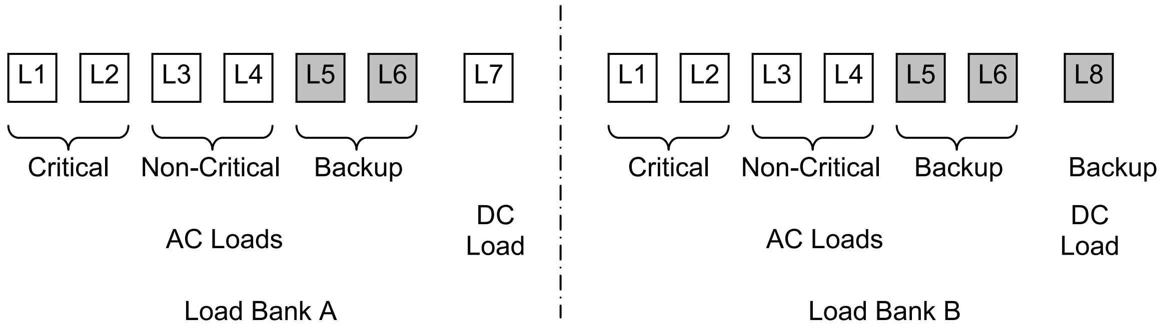
- On Load Bank B,
  - If the only one of the backup loads (L5 or L6) is turned on, one of the non-critical loads (usually L4) must be turned off. (Figure 4-2 (c))
  - If both AC bus backup loads (L5 & L6) are turned on, both non-critical loads (L3 & L4) must be turned off. (Figure 4-2 (d))

Variation: It is possible for a single battery to power two load banks at the same time. (However, it is NOT allowed for more than one battery to feed a single load bank.) To do this, first, turn off all the non-critical loads on both load banks (L3 & L4 on both load banks). Then, turn on up to two critical AC loads per each load bank. (See Figure 4-2 (e))

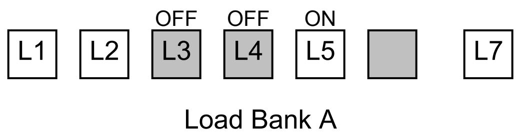
In any case, you should no shed the DC load (L7 or L8). The DC load, L7, is a critical ECLSS load that controls the cabin air pressure. Thus, either the primary (L7) or its backup (L8) should be on all the time.

4.5 Diagnosing Failure

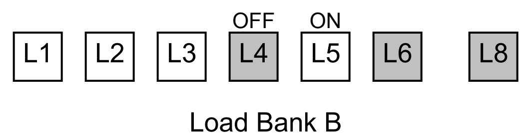
The EPS fault management process generally consists of two processes: diagnosis and recovery. Let us take a look at the diagnosis process first. The EPS is equipped with a number of sensors, and when a sensor reading goes out of the predefined normal range, it triggers a corresponding C&W message. The failure of an upstream component may result in the loss of power to all the downstream elements connected to it, which will produce a flood of C&W messages, even though the downstream elements would function correctly if they were supplied with power. The highest level failure is denoted the root cause, because if its failure can be mitigated, the



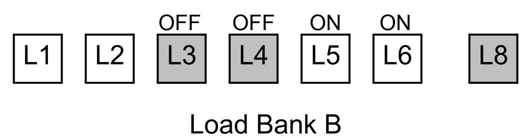
(a) Nominal Condition



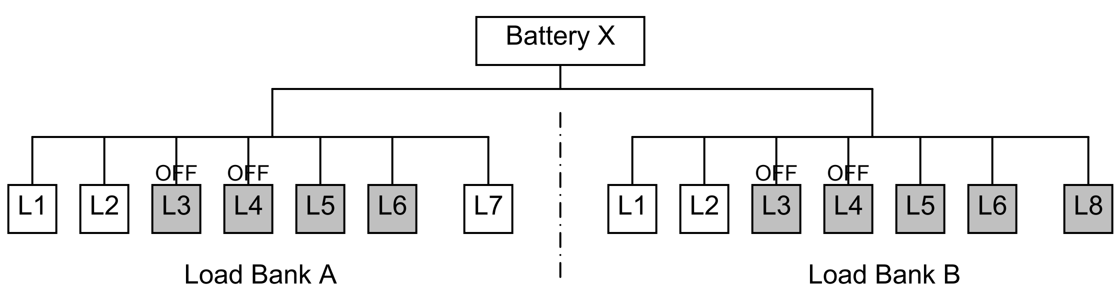
(b) Turning on One or Two Backup Loads on Load Bank A



(c) Turning on One Backup Load on Load Bank B



(d) Turning on Two Backup Loads on Load Bank B



(e) A Single Battery Powering Both Load Banks

Figure 4-2. Load Shedding Rules

downstream elements (symptoms) will be re-supplied with power and will function correctly. Your task is to diagnose and identify the root cause that is producing the symptoms.

Usually, the most upstream component triggering a C&W message has the root cause.Table 4-2 may be useful in determining which message is more upstream than the others. In this table, a component above is more upstream than the components below. (Compare the table with Figure 4-1 also.) The C&W messages related to amperage ("amps") are not as reliable for the purpose of identifying the failed component, because the upstream current could be affected by a failed downstream component.

Table 4-2. EPS Caution & Warning Messages for Root Cause Diagnosis

Component	C&W Messages	Component	C&W Messages
Battery X	Battery X volts low		
Battery X Out	Battery X Out volts low Battery X Out amps low/high		
DistXY sw	DistXY sw mismatch		
Load Y Bus	Load Y Bus volts low		
LoadY sw	LoadY sw mismatch		
Load Y	Load Y volts low Load Y amps low/high		
AC Bus Y	AC Bus Y V1 volts low (*1) AC Bus Y V2 volts low (*2) AC Bus Y amps low/high AC Bus Y freq low/high (*3)	DC Bus Y	DC Bus Y volts low DC Bus Y amps low/high
L1 - L6 AC load sw	L# sw mismatch	L7 or L8 DC load sw	L# sw mismatch

(*1) The voltage between the Inverter Y and the circuit breaker, Dist 6 or Dist 9.
(*2) The voltage between the circuit breaker, Dist 6 or Dist 9, and the AC load switches.
(*3) Inverter frequency.

Notice that the C&W messages in Table 4-2 are still the symptoms ("volts low," "amps high," etc.), not the root cause itself. The root cause is usually a failure of a particular physical component, such as "battery failure," "switch failed off," "circuit breaker tripped," etc. Also note that the C&W message could be a false alarm caused by a failed sensor. For instance, a message like "such-and-such sw mismatch" could be just a failure of the switch-position sensor. If it were merely a sensor failure, then the downstream C&W messages symptomatic of a real switch failure would not be present. Thus, once you receive a C&W message, or a symptom, you still need to diagnose the root cause based upon the overall messages you receive.

How you conduct the root-cause diagnosis will be quite different depending on which ACAWS displays you are using. The two displays, Elsie and Besi, were designed based on two different philosophies. Elsie is designed to present *complete* information to the operator, while Besi is designed to automatically suppress the unnecessary details and provide *compressed* information to the operator. More details of each display will be explained in the next ACAWS Display sections in Volume 2, but here are nutshells.

If you are using Elsie, it presents all the C&W messages issued (*complete* information), and you must diagnose the root cause and select the relevant checklist. First, you must determine via EPS displays or the ECLSS display the most upstream component that is having problems. Then second, you search the Fault Log display to find the corresponding C&W message. Third, you manually navigate the checklist index to find the checklist with a title corresponding to the C&W message. For instance, if you think “Battery A Out volts low” is the most upstream C&W message (i.e., the *Battery A Out*, a segment between the Dist 1 cb and DistAA sw is the most upstream component that issued the C&W messages), go to the “Battery A Out volts low” checklist. The first part of the checklist procedure assists with this diagnosis, which typically includes checking downstream and/or upstream sensor readings. These steps help you identify the failed component (including a failed sensor). For instance, if the downstream sensor shows a nominal value, then the problem is probably a false alarm due to a sensor failure. Or, another example is that, if the upstream sensor indicates an out-of-limit value as well, that means you did not choose the most upstream symptom. In that case, you will be re-directed to another checklist corresponding to the upstream component. Once the root cause is identified, the checklist will walk you through the proper isolation and recovery procedures.

If you are using Besi, the process would be different. Besi is equipped with an automatic model-based diagnosis engine that computes the most likely root cause and presents it to you (*condensed* information) in the Root Cause Area. The C&W messages are still available in the Fault Message Area. After you select the root cause, Besi will automatically bring up the proper checklist procedure. The first part of the checklist is the diagnosis – similar to the Elsie checklists. However, since Besi’s diagnosis engine has already checked the consistencies among multiple sensor readings, only a minimum amount of diagnosis is required by the operator. As a result, the Besi checklist typically contains fewer procedures (more like a verification of the automatic diagnosis result) due to elimination of the diagnostic steps included in the Elsie checklist (actual troubleshooting). Once the root cause is confirmed, the second part of the checklist guides you through the proper recovery process.

4.6 Recovering from Failure

There are only three types of EPS recovery procedures: 1) turn on a backup load, 2) change power source, and 3) combine critical power sinks. The EPS system is designed with several levels of redundancies to prevent loss of any critical loads. The three procedures utilize the redundancies at different levels. In both Elsie and Besi, the checklist will walk you through the recovery procedures appropriate for the situation, so you do not need to memorize them. However, understanding the differences among them may help you maintain better situation awareness.

1) Turn on Backup Load

The following root causes result in loss of a single critical load, while the rest of the EPS is fine:

- A load switch for a critical load failed open (i.e., the switch is stuck at the open position), or
- Physical or mechanical failure of a critical load itself.

In this case, simply switch to the backup of the critical load on the other load bank. The general procedure is as follows:

1. Turn OFF the load switch to the bad critical load.

2. Before switching to the backup on the other load bank, follow the appropriate load-shedding rule and turn off some non-critical loads as required.
3. Turn ON the backup critical load.

2) Change Power Source

An irreparable part of the power supply to the system is lost when the following failures occur:

- A battery failure
- A <u>DistXY</u> sw failed open, or
- A circuit breaker (Dist1, Dist2, or Dist3) has tripped.

In this case, you can switch the power source to the backup battery (usually Battery C).

1. Turn OFF all the AC and DC loads connected to the affected load bank (Y) to prevent high inrush current when the load bank gets power back.
2. Turn OFF <u>DistXY</u> to disconnect the affected load bank (Y) from the bad battery (X).
3. Turn ON <u>DistCY</u> to connect the affected load bank (Y) to the backup battery (Battery C).
4. Turn ON the AC and DC loads on the affected load bank (Y) as required.

3) Combine Critical Power Sinks (2 Banks)

This is the case where both load banks were used initially (2-bank operation), and there is a lose of one of the load banks, or a loss of either the AC or DC buses. The batteries are still working fine. Such a situation is caused by:

- The <u>LoadY</u> sw failed open (bus loss),
- A circuit breaker (any of Dist4 through Dist9) has tripped (AC bus loss or DC bus loss), or
- An inverter Y shut down (AC bus loss).

In this case, you will shut down the bad bus, and turn on the backup on the other load bank. The difference from 1) is that you will be left with only one operational load bank.

1. Turn OFF all the loads on the affected bus (AC bus Y, DC bus Y, or both).
2. If an entire load bank had failed, turn OFF <u>LoadY</u> to disconnect the affected load bank (Y).
3. Before switching to the backup on the other load bank, follow the appropriate load-shedding rule and turn off some non-critical loads as required.
4. Turn ON the backup critical loads.

Note there is also a procedure called "Combine Critical Power Sinks (1 bank)." This is for 1-bank operations, where only one load bank is initially used. All our trials are 2-bank operations, and thus, please always choose the "… (2 banks)" procedure.

4.7 Initialization Procedure

Occasionally, we may ask you to conduct the EPS startup procedure. In that case, you can call up the Initialization Procedure in the checklist and follow the instructions. The outline of the procedure is as follows:

1. Turn ON DistAA
2. Turn ON DistBB
3. Turn ON LoadA
4. Turn ON LoadB
5. Turn ON AC and DC critical-load switches on the Load Bank A (L1 through L4 and L7)
6. Turn ON AC and DC critical-load switches on the Load Bank B (L1 through L4 and L8)

4.8 Self-Check Quiz - EPS

1. During the ascent, the batteries cannot be re-charged. (true / false)
2. The EPS consists of 3 sections, Generation, Storage, and Distribution. (true / false)
3. Which battery is usually used as a backup battery? ___________
4. How many load banks are in the EPS? ____
5. DistAB switch connects Battery (A, B) to Load Bank (A, B).
6. Which AC load(s) is/are the critical load(s) on each AC Load Bank? (L1, L2, L3, L4, L5, L6 – mark all that apply)
7. Which AC load(s) is/are the nominal load(s) on each AC Load Bank? (L1, L2, L3, L4, L5, L6 – mark all that apply)
8. Which DC load is the critical one? (L7 / L8)
9. Which load is the backup of L2 on Load Bank A? (L___ on Load Bank ___)
10. Freon Loop primary (P) critical loads are powered via the Load Bank B. (true / false)
11. The notation, "sw," is an abbreviation of __________.
12. The notation, "cb," is an abbreviation of __________.
13. Among the C&W messages you have received, these three messages were associated with the most upstream components. Which component most likely failed? (mark one)

    Battery A Out amps low, DistAA sw inconsistent, Load A Bus volts low
14. You have lost one critical load on Load Bank A. You are turning on its backup on the Load Bank B. How many non-critical load(s) on the Load Bank B should be shed before turning on the backup? _____
15. You have lost the entire Load Bank A. You are turning on the backups on the Load Bank B. How many non-critical load(s) on the Load Bank B should be shed before turning on the backups? _____
16. You have lost one critical load on Load Bank B. You are turning on its backups on the Load Bank A. How many non-critical load(s) on the Load Bank A should be shed before turning on the backup? _____
17. You have lost the entire Load Bank B. You are turning on the backups on the Load Bank A. How many non-critical load(s) on the Load Bank B should be shed before turning on the backups? _____

18. A single battery can power more than one load bank. (true / false)

19. More than one battery can power a single load bank. (true / false)

20. You have lost two batteries. Thus, you have decided to use a single battery to power two load banks at the same time. How many non-critical loads these two load banks can continue powering? _____

21. Which component is/are user-controllable? (mark all that apply)

    Circuit Breaker   Inverter   Switch

22. Different ACAWS displays (Elsie and Besi) have different EPS fault management procedures. (true / false)

23. When Battery A failed (and it has been used to power Load Bank A), which type of recovery procedures you should perform? (mark one)

    Turn on a Backup

    Change Power Source

    Combine Critical Power Sink (1 Bank)

    Combine Critical Power Sinks (2 Banks)

24. When AC Bus B is lost due to LoadB sw failed open, which type of recovery procedures you should perform? (mark one)

    Turn on a Backup

    Change Power Source

    Combine Critical Power Sink (1 Bank)

    Combine Critical Power Sinks (2 Banks)

Appendix A: Answers to Self-Check Quiz

ECLSS

1. *False*. See Figure 3-1. The unmarked parameters are non-supported. That means our EPS-ECLSS model does not include these parameters. During the simulation, the non-supported parameters stay near their nominal values.

2. *False*. The C&W message area of the ACAWS displays will indicate a C&W message if an ECLSS parameter goes off-nominal. (This has not been mentioned in the ECLSS section, but the EPS displays of the ACAWS displays also contain indirect status information of the ECLSS loads.)

3. *True*. If an ECLSS parameter turned to red, that means this is a critical parameter. Thus, any red indication means that corresponding ECLSS load, which is critical to the maintenance of the habitable environment in the crew cabin and/or operational condition in the avionics bay, has a failure. Note that the red indication could also be a false alarm caused by a sensor failure. The checklist procedure will assist you diagnose the root cause including a sensor failure.

4. *False*. Critical parameters never turn to yellow. They always turn to red. Non-critical parameters turn to yellow when they show off-nominal values.

5. *3*. Evap Out T1, Evap Out T2, and Evap Out T3 are redundant sensor measurements of a single value, the flash evaporator outlet temperature.

6. *False*. Av Bay Temp (not Cabin P) value and Evap Out T values are positively correlated.

7. *True*. All parameters in the ECLSS display are measured by sensors. Thus, there is always a possibility that any off-nominal indication is caused by a sensor failure, until the situation is disambiguated by a proper checklist procedure. (Usually, checking with the downstream sensors will verify if this is a sensor failure or not.)

8. *True*. The Av Bay Fan Switch configuration at the top reflects the system (P or BU) by which the first critical load within the area – in this case, the avionics bay fan (*Av Bay Temp*) – is currently powered. However, there is no indication about which system (P or BU) the second critical parameter within the area – in this case, the cabin fan (*Cab Fan ΔP*) – is powered. The same is true for the Water Loop area in the ECLSS display.

9. *True*. Elsie and Besi use the same ECLSS display formats.

EPS

1. *True*. The batteries can be re-charged only after getting to the orbit, where the solar panels can be deployed for re-charge.
2. *False*. The EPS consists of 4 sections (not 3), Generation, Storage, Distribution, and Loads.
3. *Battery C*.
4. *2*. Load Bank A and Load Bank B.
5. *A*, *B*.
6. L1, L2, L5, L6. See Table 4-1.
7. L1, L2, L3, L4. See Table 4-1.
8. L7 on Load Bank A. See Table 4-1.
9. L6 on Load Bank B. See Table 4-1.
10. *False*. Water Loop (not Freon Loop) primary (P) critical loads are powered via the Load Bank B. The P critical loads of the rest (Freon Loop, Fans, and Atmosphere) are all powered via the Load Bank A.
11. *Switch*.
12. *Circuit breaker*.
13. *DistAA sw*. An "amps low" in a upstream component could be caused by a downstream component. Thus, any C&W messages related to amps are not reliable indicators of the root cause location. Of the two remaining, the DistAA sw is more upstream than the Load A Bus (See Table 4-2). Therefore, the DistAA sw is the most likely component that failed. (Note: you see any C&W message related to a switch inconsistency or failed off, that is usually the #1 candidate of the root cause.)
14. *1*. See the section, 4.4Load Shedding. You are turning on one backup on Load Bank B.
15. *2*. See the section, 4.4Load Shedding. You are turning on two backups on Load Bank B.
16. *2*. See the section, 4.4Load Shedding. You are turning on one backup on Load Bank A.
17. *2*. See the section, 4.4Load Shedding. You are turning on two backups on Load Bank A.
18. *True*.
19. *False*. The ACAWS displays will also prevent you from doing this. For instance, if <u>DistAA</u> sw is closed, then the displays will not let you close <u>DistBA</u> nor <u>DistCA</u> sw. However, it still allows you to close DistAB sw (so that Battery A can feed to both load banks at the same time).
20. *None*. If a single battery is powering the both load banks, all non-critical loads must be shed beforehand.
21. *Switch*.
22. *True*. Because Besi's automatic diagnosis software already checks the sensor value consistencies, the operator does not have to perform the complete troubleshooting routine. This makes the fault management procedures different between Elsie and Besi.

23. Change Power Source. It's a battery-loss case. You need to switch to the backup battery.
24. Combine Critical Power Sinks (2 Banks). It's an AC-bus-loss case. Thus, you need to move the critical AC loads to the other operating AC bus. Our initial configuration is always the 2-bank operation mode; thus, always pick the "… (2 Banks)" procedure.

Appendix B: Glossary

AC	Alternating Current
ACAWS	Advanced Caution and Warning System
ADI	Attitude Director Indicator (PFD)
Accum Qty	Accumulator Quantity
ACK	Acknowledge
amps	amperage
Av	Avionics Bay
Av Bay	Avionics Bay
BU	Backup
C&W	Caution and Warning
Cab	Cabin
Cabin P	Cabin Pressure
cb	Circuit Breaker
CEV	Crew Exploration Vehicle
CP	Cold Plates
DC	Direct Current
ΔP	Delta P (change in pressure)
dP/dt	Delta P / Delta t (change in pressure)
ECLSS	Environmental Control and Life Support System
EPS	Electrical Power System
Evap Out T	Flash Evaporator Output Temperature
FES	Flash Evaporator System
H Sit	Horizontal Situation Display (PFD)
HX	Heat Exchange
Ich	Interchange
IMU	Inertial Measurement Unit
In	Inlet
Isol Vlv	Isolation Valve
LAS	Launch Abort System
MET	Mission Elapsed Time

Mgmt	Management
msg	Message
N2	Nitrogen (N_2)
NH3	Ammonia (NH_3)
O2	Oxygen (O_2)
Out	Output
P	Primary
P	Pressure
PL	Payload
ppO2	Partial Pressure of Oxygen
PCS	Pressure Control System
PFD	Primary Flight Display
PV	Photovoltaic
Rad	Radiator
SM	Service Module
Sum	Summary
sw	Switch
T	Temperature
tb	Talk back (actual position of the switch or circuit breaker)
Temp	Temperature
Vert Sit	Vertical Situation Display (PFD)

Evaluation Study for Crew Exploration Vehicle (CEV) Advanced Caution and Warning System

Participant Training Manual

Volume 2 of 2

Intelligent Spacecraft Interface Systems (ISIS) Lab &
Advanced Diagnostics and Prognostics Testbed (ADAPT) Lab
NASA Ames Research Center

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Table of Contents
Volume 2

5 Advanced Caution and Warning System (ACAWS) Displays

5.1 ACAWS Displays Overview

This section describes the one of the actual displays that you will use to monitor and manage the EPS and ECLSS. These displays were developed under the Advanced Caution and Warning System (ACAWS) project. So, we call them "ACAWS displays" in this study. The ACAWS displays were originally designed to provide crew interface to the health of the entire spacecraft systems. However, in this experiment, only the parts related to the EPS and ECLSS are activated.

There are two different ACAWS displays, Elsie and Besi, designed with two different philosophies. Elsie can be likened to interactions with an engineer. The philosophy behind Elsie is to present all the information to the crew and allow them to make decisions without requiring extra steps to expose the details. In other words, Elsie presents *complete* information to the user. In contrast, Besi can be likened to interactions with a manager. The philosophy behind Besi is to summarize as much information as possible. Details are available but hidden from view unless requested by the crew. In other words, Besi displays *condensed* information to the user. During a given mission, only one display, either Elsie or Besi, can be run on board the vehicle.

5.2 Input Device for the ACAWS Displays

The same input device is used for both Elsie and Besi. In both displays, ACAWS functionality is available via selecting edge keys and buttons shown on the display. For instance, Figure 5-1 shows an example of display edge keys, where two buttons are active (bright green; *System Focus* and *Checklist*), two are inactive (dim green; *Ack* and *Fault Log*), and two are blank. Your current focus is on *Checklist* (gray highlight).

Figure 5-1. Navigating within Edge Keys

Both Elsie and Besi utilize a discrete one-dimensional travel method for the focus navigation. Use the arrow keys on the Nostromo hand controller (See Figure 5-2) to navigate the focus to an edge key. The edge keys are on a circular list that can be traveled in either direction allowing the crewmember to decrease the path length as desired. For instance, from the position in Figure 5-1, you can push the right key once to go to the *System Focus*, rather than pushing the left key three times (blank edge keys are skipped). To select a highlighted key, press the *Select* button on the Nostromo, the black rectangular key directly in front of the arrow keys (Figure 5-2). You can select only active edge keys indicated with bright green texts. The round orange button can be used to silence the Master Alarm sound.

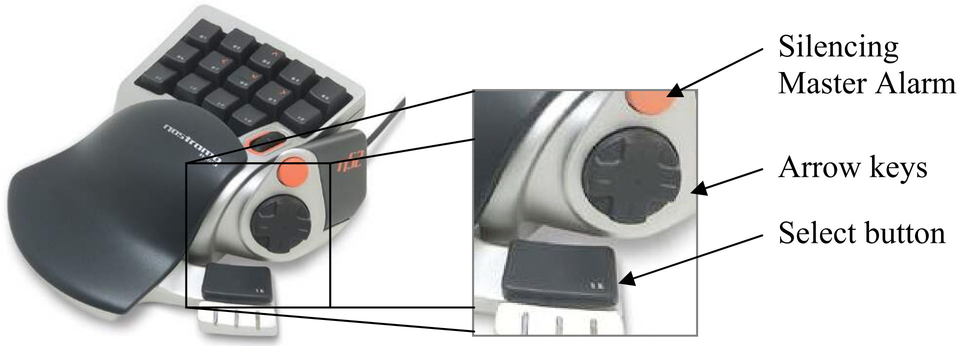


Figure 5-2. Nostromo Hand Controller

5.3 Common Displays

1) ECLSS Display

The ECLSS display that indicates the ECLSS parameters is shared between Elsie and Besi. See the ECLSS section (in volume 1) for more details. The edge key operations to bring up the ECLSS display are slightly different between Elsie and Besi, and will be explained in the Elsie and Besi sections, respectively.

2) Fault Sum

The Fault Summary display, or Fault Sum, presents an at-a-glance summary of the status of all critical spacecraft systems, such as the ECLSS and the EPS (Figure 5-3). This is a good display to view to maintain awareness of the state of critical systems when you are not resolving any particular problem, such as the very beginning of a trial. Fault Sum also provides information of the other Orion subsystems, such as the Data Processing System (DPS), the Guidance, Navigation and Control (GNC) system, the Reaction Control System (RCS), the Orbital Maneuvering System (OMS), the Main Propulsion System (MPS), and the Auxiliary Power Unit Hydraulics (APU Hyd). However, again, only the ECLSS and the EPS status information is populated in the ACAWS displays in this experiment.

Within the ECLSS area (upper-left area), the indicators, *P* (primary), *BU* (backup), and *OFF* (none), provide information about which systems is providing the power to the individual ECLSS critical components. For example, in Figure 5-3, the *Cabin P* is running on the backup system. If a problem is detected in any of the critical parameters in these ECLSS components, the corresponding indicator will change its color to red or yellow reflecting the criticality of the detected fault. In Figure 5-3, the red *OFF* indication at the Cabin Fan means this component is currently powered by neither P nor BU, and there is a warning message associated with the off-nominal reading of the Cabin Fan parameter. The red *P* indicator at the Water Loop means that the both of the two critical loads of the water loop (pump and the bypass valve – see the ECLSS section) are powered by the P, and either or both of the water-loop critical parameters are indicating off-nominal values (the EPS area explains why – remember the water loop's primary components are powered by the load bank B). Additionally, the Freon loop evaporator outlet temperature (*Evap Out T*) values are always available in the ECLSS area. In any case, **if there any red indicators in the ECLSS area, that means you have a problem.**

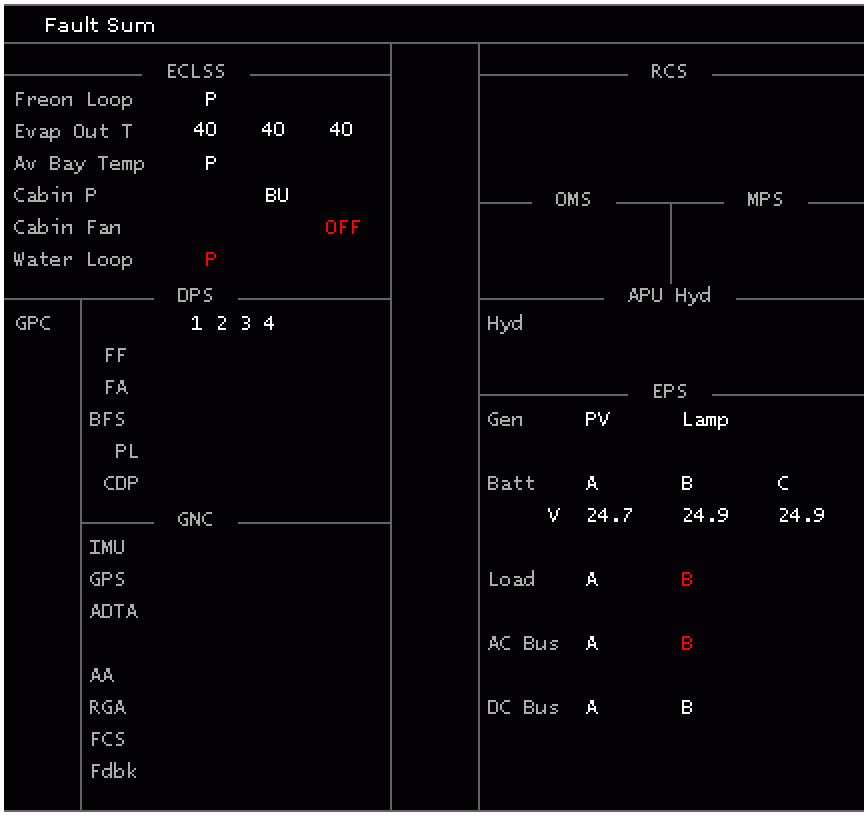


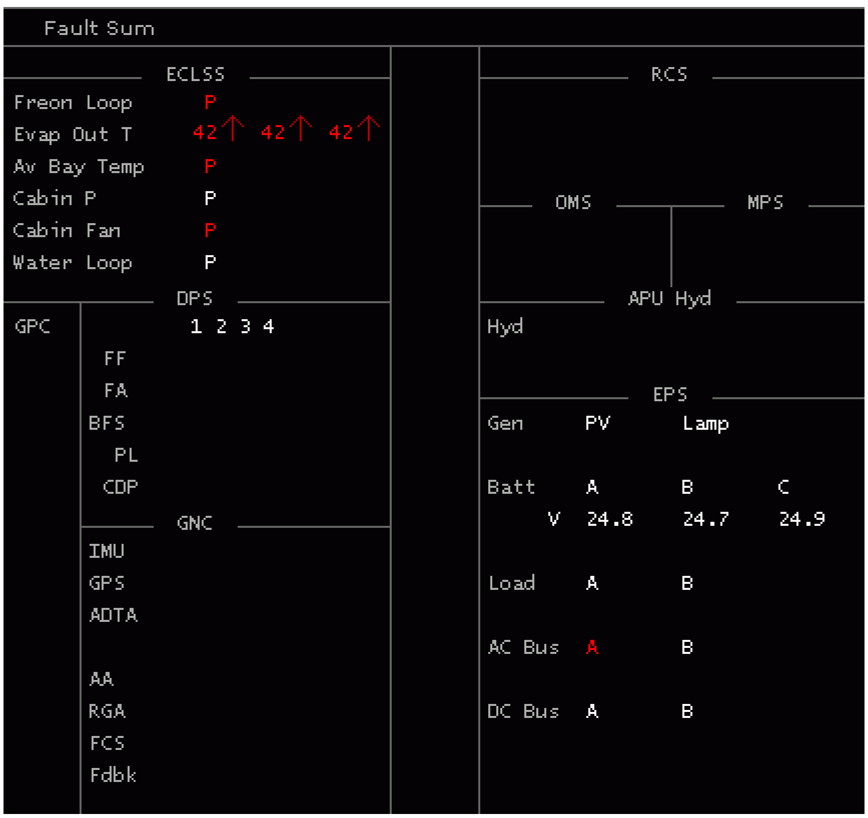
Figure 5-3. Fault Sum

Similarly, within the EPS area (lower-right area), if a problem is detected in any of the parameters, the corresponding indicator will change to red or yellow. The area is divided into the major areas of the EPS: power generation (*Gen*), batteries (*Batt*), load banks (*Load*), and AC and DC buses (*AC Bus*, *DC Bus*). For *Gen*, if any parameters associated with the photovoltaic (*PV*, a.k.a. solar panel) or lamps go out of limits, the *PV* or *Lamp* will change color. For *Batt*, if any parameters associated with a specific battery go out limits, the letter A, B, or C (mapped to Battery A, B, C, respectively) will change color. Additionally, the voltage for each battery is always available. If the value goes out of limits, its color changes and an up or down arrow appears to show that the value is above or below the limit, respectively. For *Load*, if any parameter associated with either load bus or load bank goes out of limits, the color for the corresponding load (A or B) changes. Finally, if any parameter on the AC Bus leg or the DC Bus leg goes out of limits, the color for the corresponding leg changes.

The Fault Sum is shared by Elsie and Besi. The edge key operations to bring up the Fault Sum are slightly different between Elsie and Besi, and will be covered in the following Elsie and Besi sections, respectively.

5.4 Self-Check Quiz – ACAWS Displays

1. There are three displays shared by Elsie and Besi. (true / false)
2. Which display is recommended to monitor when you are not working on any particular problem? (ECLSS display / Fault Sum)
3. Having any red indicator in the ECLSS area in the Fault Sum means that you will likely face a life-threatening condition shortly (except a case of sensor failure). (true / false)
4. (See figure.) The red *P* indicator at Av Bay Temp in the ECLSS area means that the avionics bay fan is currently powered by its primary system, and the Av Bay Temp parameter is showing an off-nominal value. (true / false)
5. (See figure.) Since ECLSS area shows more red indicators, you should fix the ECLSS problems first before fixing the EPS AC Bus problem. (true / false)



6 Elsie

6.1 Complete Approach for Information Presentation

Elsie takes the *complete* approach, which is presenting all of the information to the crew and enabling direct manipulation of switches on switch panels. The approach is applied to both C&W message presentation and procedure instruction for fault management (i.e., both diagnosis and recovery).

C&W messages are generated for each parameter that goes out of a pre-determined nominal range of the value. If a fault causes multiple parameters to exit their nominal range, multiple messages will be generated. As described in the EPS section, the crew uses these messages to diagnose the root cause of the fault and then selects the appropriate procedure from the checklist index. The procedure either concurs with the crew's assessment or, if the actual symptoms are inconsistent with the expected symptoms, guides them elsewhere (via troubleshooting instructions in the diagnosis part). With Elsie, the crewmember has all the details regarding what has gone out of limits and can use those details to determine the cause of the fault.

6.2 Elsie Display Details

1) Start Page

When Elsie begins, the crew sees a mostly dark screen (Figure 6-1). If all continues to be well with the systems, the screen will remain dark. The Mission Elapsed Time (*MET*) is displayed at the upper-right corner. The display is divided into three areas, surrounded by edge keys. The Main Area (upper left) is where the system list, system schematics, data displays, and fault log display appear. The Checklist Area (upper right) is where electronic checklists appear. The Message Area (bottom) is where C&W messages appear. At start-up, there are three selectable edge keys: *System Focus*, *Fault Sum*, and *Checklist Index*. The *Master Alarm*, *ACK*, and *Fault Log* buttons are dim and, thus, not initially selectable. When other displays or checklists are brought up, additional edge keys appear and are used to navigate within that display.

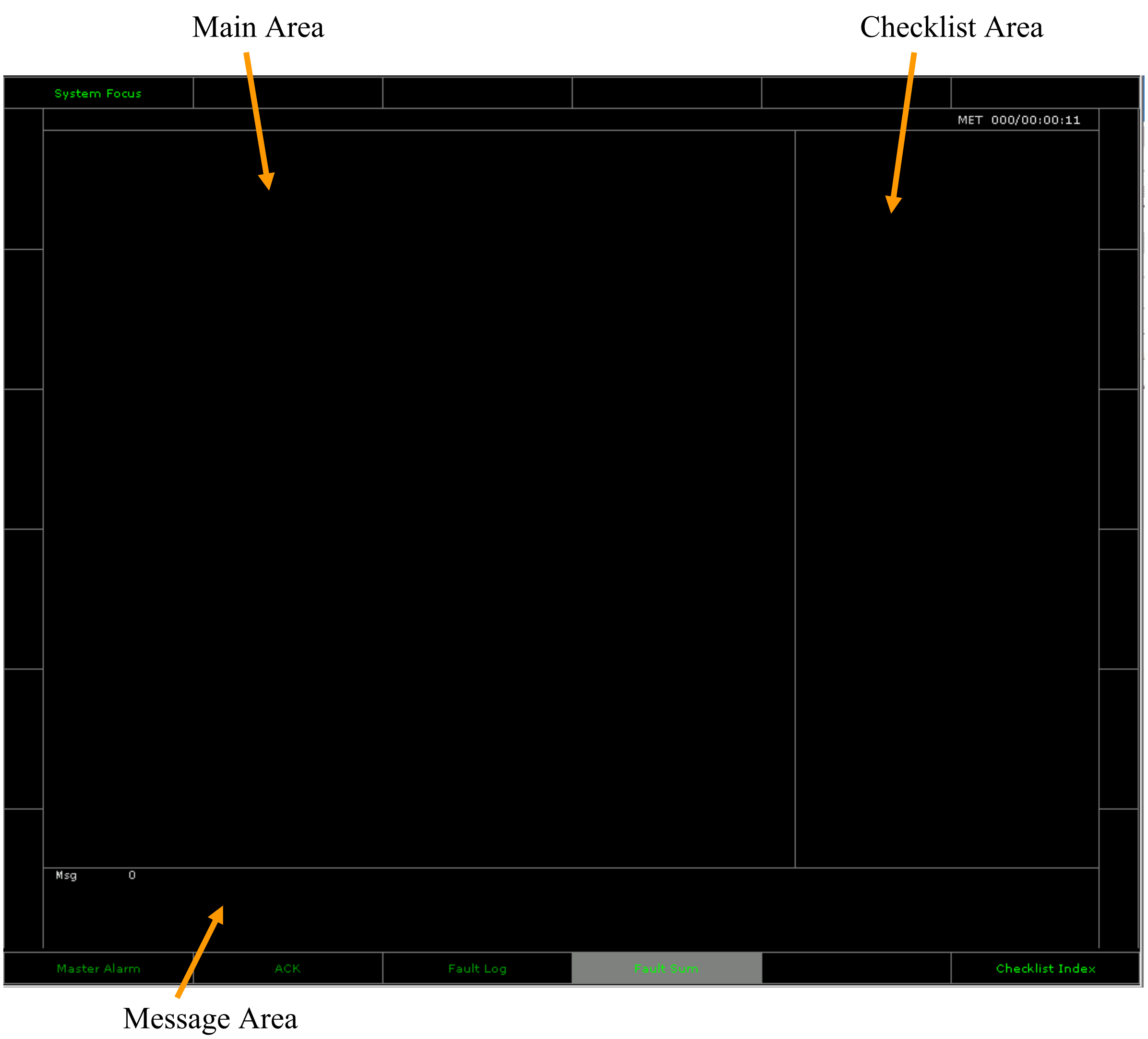


Figure 6-1. Elsie Start Page

2) Fault Sum

The details of the Fault Sum display have been described in the ACAWS section. In Else, selecting *Fault Sum* edge key will bring up the Fault Sum display in the Main Area. When Elsie starts, the *Fault Sum* edge key is focused in the Start Page (as seen in Figure 6-1).

3) System Focus

When the Fault Sum shows color changes in a certain system (EPS or ECLSS in this experiment), you may want to go to check more details of these systems. The System Focus function lets you move among Orion systems. After selecting the *System Focus* edge key in the upper-left corner, the edge-key text turns from green to white to show that the focus of the hand controller is now inside the System Focus area (see Figure 6-2). It also has a dot next to the text to provide an additional cue. The blue focus bar highlights the current focus of the hand controller. To select a different system, arrow up or down (remember it's a circular list) to the desired system and press the Select button on the hand controller. (In this experiment, only EPS and ECLSS are activated. Selecting other systems will lead you to an empty page.) To return focus to the edge keys without changing the currently selected system, either select the same system or select the bottom *Return to Edge Keys* button.

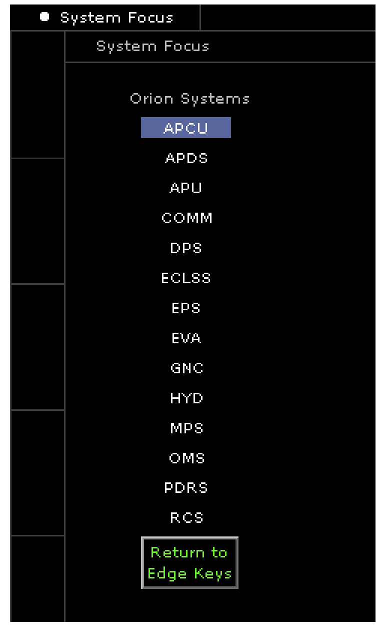


Figure 6-2. System Focus

4) ECLSS Display

When you select the *ECLSS* on the System Focus, the ECLSS display appears in the Main Area. This is how to call up the ECLSS display in Elsie. The ECLSS display is shared by Elsie and Besi. Refer ECLSS section and ACAWS section for more details.

5) EPS Display

When you select the *EPS* on the System Focus, the EPS display appears in the Main Area. The EPS display provides information about the EPS including such things as charge status of the batteries, the connectivity between chargers and batteries and between batteries and loads, and the status of connectivity from the batteries to the spacecraft systems. Elsie uses different EPS display from Besi. The major difference is that, as mentioned before, Elsie takes the complete approach to provide the EPS information. It presents digital values of all the important EPS system parameters. Elsie also separates the controlling task from the monitoring task by separating EPS control switch panels from the EPS system schematics.

When the *EPS* is selected in the System Focus, eight new edge keys appear. (See Figure 6-3 for the edge-key arrangement. Note that, when the EPS is selected, the Main Area initially shows a blank screen.) Four edge keys to access the switch panels appear along the left side of the display and another four edge keys to access other details about the EPS appear along the top besides the *System Focus* key.

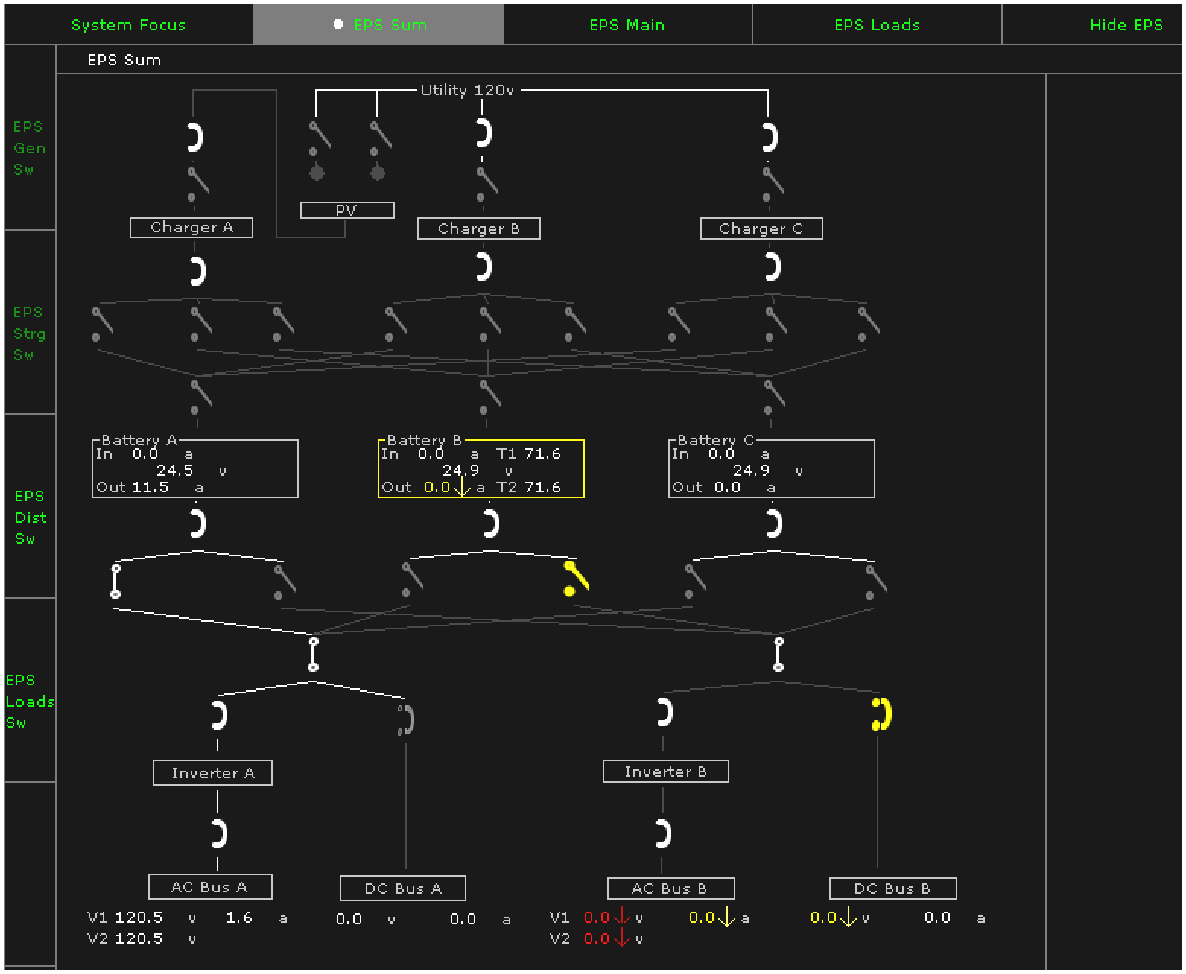


Figure 6-3. Elsie EPS Sum Display

The three edge keys on the top are used to call up three EPS displays in the Main Area: a schematic display (EPS Sum), a textual display of all EPS parameters (EPS Main), and a textual display of information about the Loads level of the EPS (EPS Loads). Selecting the fourth edge key, *Hide EPS*, returns the display to a dark screen.

An example of the EPS Sum display is shown in Figure 6-3. The schematics shows the Generation level components from the utility power connection to the three charge controllers, the Storage level components from below the chargers to the batteries, and the Distribution level components from below the batteries to the two DC buses and the inverters leading to the AC buses. It shows connectivity, voltage, and current throughout the system. White lines indicate that there is current flow, while gray lines indicate no current. The pairs of dots with a short straight line are switches, and the pairs of dots with an arc are circuit breakers. Switch and circuit breaker symbols in gray means they are off as commanded (i.e., they are not faults). A red or yellow switch symbol means failed off (stuck at off position), and a red or yellow circuit breaker symbol means tripped. These symbols in red or yellow are faults, and will cause C&W messages of the same color. Note that the EPS Sum display does not show the connectivity, voltage or current at the Loads level. That information is available via the *EPS Loads* edge key.

EPS Main display, which appears in the Main Area when the *EPS Main* edge key is pressed, shows numerical values for all EPS parameters on the left and the status of the switches and circuit breakers through the system on the right. (Figure 6-4) In this experiment, you will need to monitor only the three blocks: the *Battery* block (middle left) showing the battery parameters (i.e., voltage in, battery voltage, voltage out, current in, current out, and two temperatures for Battery A, B, and C), the *Loads* block (lower left) showing the load-related parameters (i.e., load bus volts, load-bank voltage, load-bank ampere, AC-bus frequency, AC-bus voltage, AC-bus ampere, DC-bus voltage, and DC-bus ampere for Load A and B), and the *Distribution Bus* block (lower right) showing the switch states in the Distribution section (i.e., Dist1-3 cbs, DistXY switches connecting Battery X to Load Y, LoadY switches, and Dist4-9 cbs). As shown in Figure 6-4, the EPS Main presents off-nominal values in colors (red or yellow) alongside with arrows indicating that the values are too high (up arrow) or too low (down arrow).

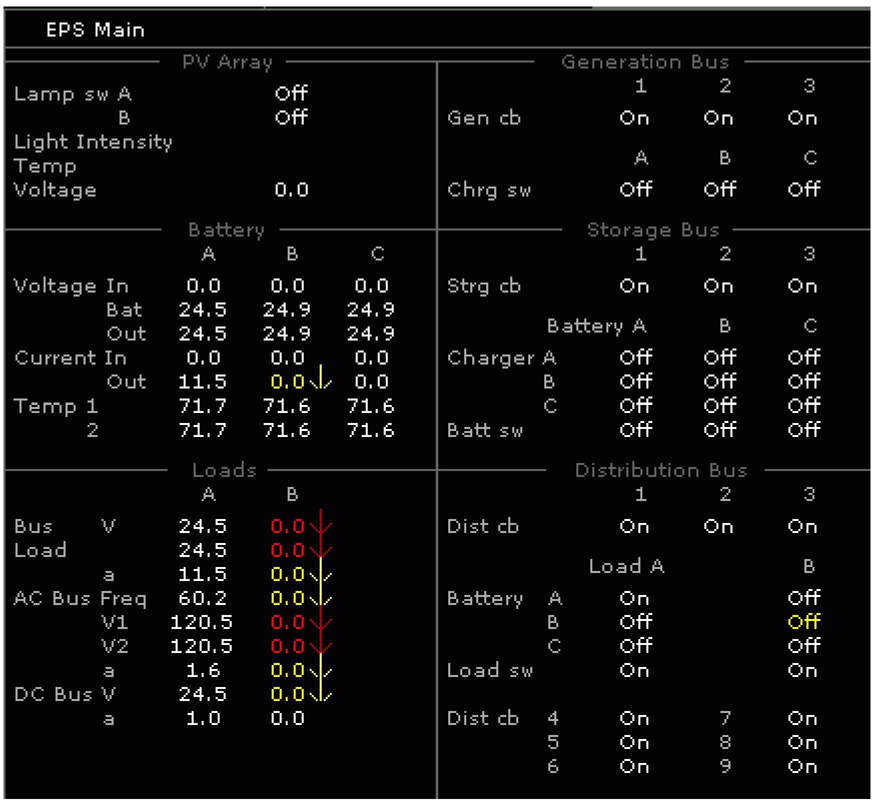


Figure 6-4. EPS Main Display

When the *EPS Loads* edge key is pressed, the EPS Loads display appears in the Main Area (Figure 6-6). This display shows the status of the switch that controls the AC Bus loads (i.e., L1 through L6, on the left) and the DC Bus loads (L7 or L8, on the right). It also shows the voltage, *V*, and current, *a*, for the A and B legs of the AC and DC buses. Like EPS Main, EPS Loads also displays off-nominal values in colors (red or yellow) and upward or downward arrows.

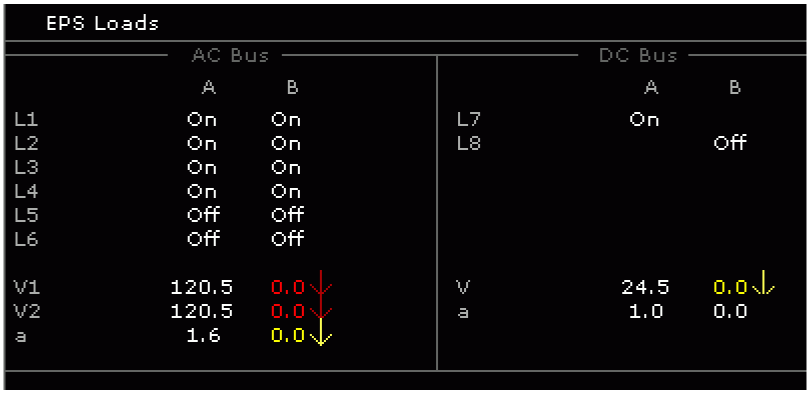


Figure 6-6. EPS Loads Display

Elsie separates information displays from switch panels. The above three displays only provide the current-status information, not the commanded-status information. In Elsie, the commanded-status information can be viewed only on the switch panels, where the crewmember can also command the switch throws. These switch panels are available via the edge keys on the left side of Elsie. In this experiment, you have access to only the two edge keys on the lower-left side, *EPS Dist (Distribution) sw* and *EPS Loads sw* panels. (The top two edge keys are disabled.) See Figure 6-3 for the edge key arrangement on the left side of the display.

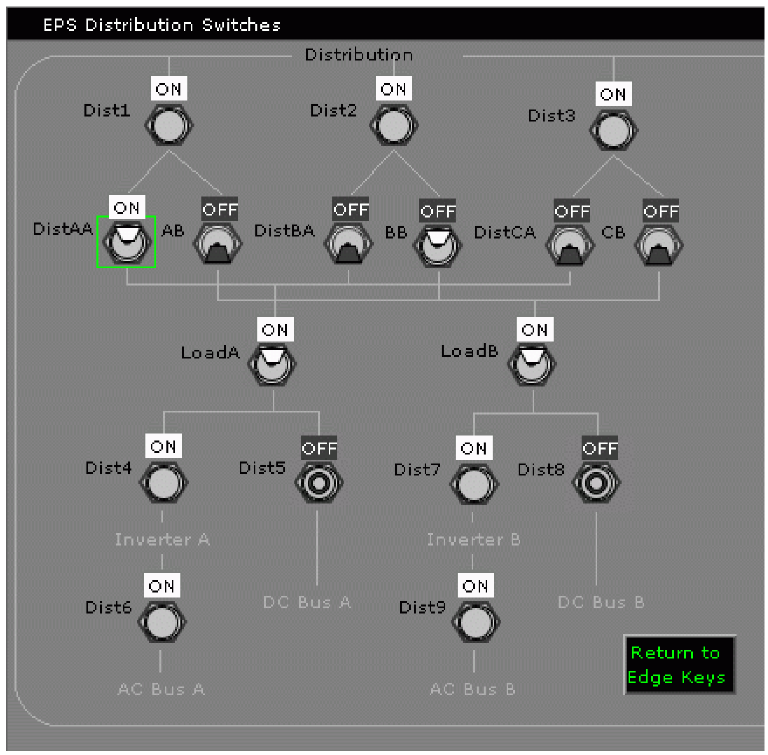


Figure 6-5. EPS Distribution Switch Panel

Figure 6-5 shows an example of the Distribution Switch Panel brought up via the *EPS Dist Sw* edge key. In Figure 6-5, the icon for a switch resembles a light switch. If the paddle points up, the switch is on. Alternatively, if the paddle points down, the switch is off. Notice that the paddle for switches that are on is white (e.g., DistAA in Figure 6-5) and the paddle for switches that are off is dark (e.g., DistAB in Figure 6-5). The icon for a circuit breaker resembles a physical circuit breaker. When the breaker is off (out), the part sticking out creates the extra circle inside the cb (e.g., Dist5 and Dist8 in Figure 6-5). When the breaker is on (in), nothing is sticking out – everything is on one level and therefore, the cb does not have the extra circle (e.g., Dist4 in Figure 6-5).

Each switch or circuit breaker has a talkback (tb) shown in the label area above the icon. **The icon itself shows the *commanded* state of the switch or the circuit breaker. The talkback shows the *actual* state of the switch or circuit breaker**, the state detected by the sensors. If the two do not match, a problem has occurred with the switch – it is either failed open (switch stuck at off position while commanded on) or failed close (switch stuck at on position while commanded off). In Figure 6-5, can you tell that DistBB sw is failed off? If a sensor sensed a mismatch between the commanded and actual switch positions, a C&W message is generated to inform the crewmember of the sw mismatch.

The green box (shown in Figure 6-5 surrounding the *DistAA* switch) indicates the current focus of the hand controller. Pressing the Select button on the hand controller will change the state of the switch that is in focus. The arrow keys on the hand controller move the focus and enable a crewmember to select a different switch to control. The left/right arrows move the focus within a single row of switches. The up/down arrows move within a single column of switches to move the focus to a different row. In Figure 6-5, to reach the *Return to Edge Keys* from the focus switch, use the left arrow to reach *DistCB* and then use the up arrow to go to the *Return to Edge Keys* (remember the focus moves circular). Pressing the Select button while focused on the *Return to Edge Keys* area will return control of the hand controller back to the edge keys. Note that the focus will not travel to any components that are not user controllable (i.e., the circuit breakers).

Figure 6-7 shows the other switch panel, EPS Loads sw panel, used to turn on or off individual AC and DC load. The switch panel appears when *EPS Loads Sw* edge key is selected. The top half is for controlling the AC load and DC load switches on the load bank A, and the bottom half for controlling those on the load bank B. The EPS Loads sw panel operates in the same way as the EPS Dist sw panel. (Can you tell that the AC bus A L2 switch is showing a mismatch?)

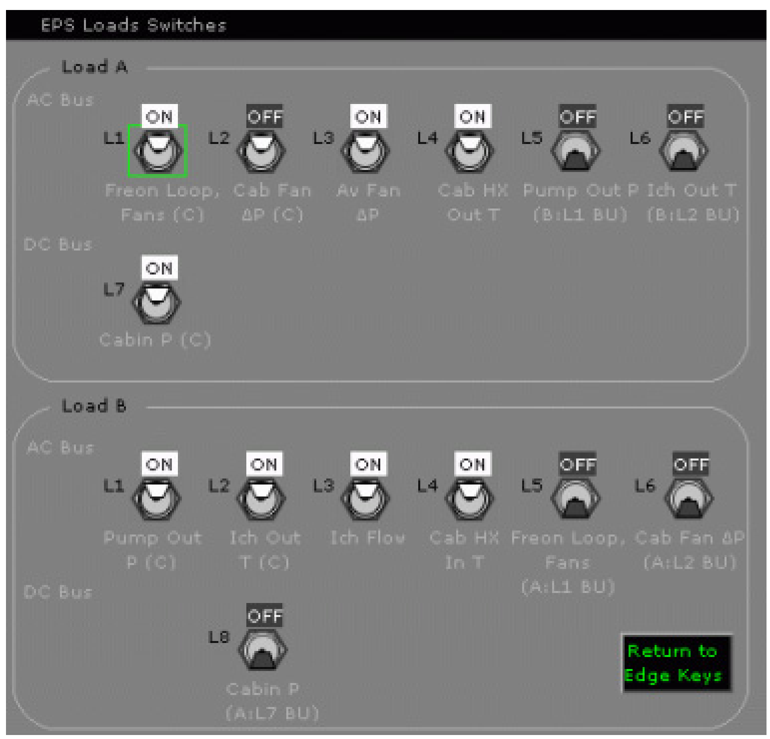


Figure 6-7. EPS Loads Switch Panel

6) Message Area

When faults are detected in either EPS or ECLSS, the Master Alarm edge key will light up red, accompanying audio will sound, and C&W messages will appear in the Message Area. Figure 6-8 shows an example. The Master Alarm can be silenced by selecting the red *Master Alarm* edge key or pressing the round orange button on the hand controller. Due to the size of the Message

Figure 6-8. Example C&W Messages

area, only the first five messages are displayed. Any additional messages will be queued and the number of messages in the queue is displayed (next to the *Msg* label). For instance, in Figure 6-8, there are 9 messages in the queue in addition to the first five shown (i.e., 14 messages in total). The color of the number waiting in the queue corresponds to the color of the most severe queued message. That is, if there is a warning message (red) in the queue, the number is shown in red. If there are only caution messages (yellow), the number is shown in yellow.

There are two methods to read the C&W messages in the queue: (1) press the *Fault Log* edge key, or (2) press the *ACK* edge key. In the Fault Log display lists all the C&W messages issued, and also, you can view more messages at once (see below). The *ACK* edge key acknowledges the five visible messages and erases them from the Message area. As a result, the next (up to) five queued messages are pushed forward in the Message Area. The queue number decrements accordingly. The queue is empty when the queue number is 0. The acknowledged messages can be still viewed on the Fault Log.

7) Fault Log

Selecting the *Fault Log* edge key allows the crewmember to see all messages in the list as well as any previously acknowledged messages (Figure 6-9). Since the Fault Log uses the Main Area to show the list, up to 18 messages can be viewed at once. There are three pages in the Fault Log. Pressing the *Fault Log* edge key cycles among the three pages. Each message is preceded by a dot colored red for warnings (related to a critical load), yellow for cautions (related to a non-critical load), and white for advisory messages. The message text also uses this scheme, except that any messages that have been acknowledged turn white (but their dots remain the original color). Each message also has a timestamp.

Figure 6-9. Fault Log

8) Checklist Navigation

Figure 6-10. Table of Contents for ECLSS Checklist

To manually bring up a checklist in Elsie, select the *Checklist* edge key at the lower right corner of the display (See Figure 6-1). If a specific system is already selected via the *System Focus*, a table of contents for the checklist associated with that system appears within the Checklist Area. For instance, Figure 6-10 shows a table of contents for ECLSS checklist. If no system is currently selected, a table of Orion systems appears (similar to the list in the System Focus, Figure 6-2) so that you can select a system.

Selecting the *Checklist* edge key also transfers the focus of the hand controller to the Checklist Area, enabling the crewmember to navigate through the table of contents down to the desired checklist. In Figure 6-10, the blue focus bar shows the current focus. Pressing an arrow key on the controller moves the focus to the next procedure. To switch to a different system, navigate down (or up – it's a circular list) to *Orion Checklists*. A list of all Orion systems appears. Also notice that a number in parentheses follows each procedure. This number is the number of the procedures under this category. For example, there are three procedures under the category, ECLSS *Evap Out T Low*. As stated in the ECLSS description, there are three redundant *Evap Out T* sensors: T1, T2, and T3. To access the procedure for, for instance, *Evap Out T2 Low*, first select *Evap Out T Low (3)* and then select *Evap Out T2 Low* from the subsequent list that appears.

Figure 6-11 shows an Elsie screenshot when the *DistBB sw mismatch* checklist procedure was called up in the Checklist area. As soon as a procedure is displayed, the hand controller focus returns to the edge keys, and the crewmember uses the new edge keys that appeared on the right-hand side to navigate within the procedure. This enables the crewmember to maintain control of navigation to other systems or inside the schematic view via the edge keys. In Figure 6-11, the *Do It* edge key has the focus.

Typically, the first line of a procedure is a display change in the form of *[Display]*. In Figure 6-11, the line, *[EPS Main]*, instructs to bring up the *EPS Main* display in the Main Area. When the blue focus bar is on a display change line like this one, the checklist edge keys on the right side are: *Skip*, *Do It*, *Up* (if applicable), and *Down*. Also, the edge keys that would be used to bring up that display are highlighted with blue text (i.e., *EPS Main* edge key in Figure 6-11). To have the computer automatically bring up the proper display, select the *Do It* edge key.

Selecting *Do It* edge key moves the blue focus bar to the next applicable instruction, and dim the previous instruction (grayed out). If any component or parameter is mentioned in an instruction line, a blue highlight is used to quickly draw the crewmember's attention to the related part in the

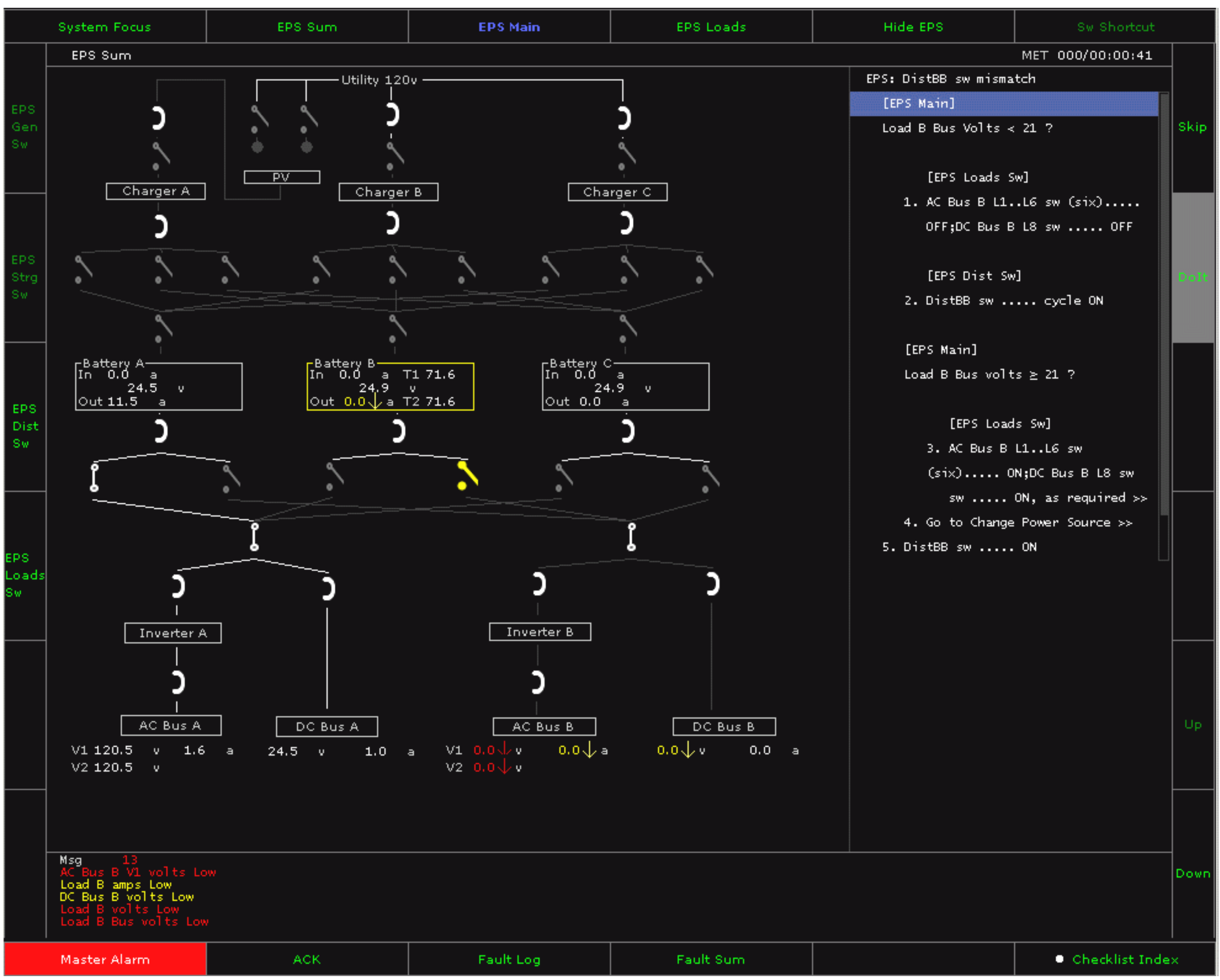


Figure 6-11. Elsie Checklist and Switch Panel

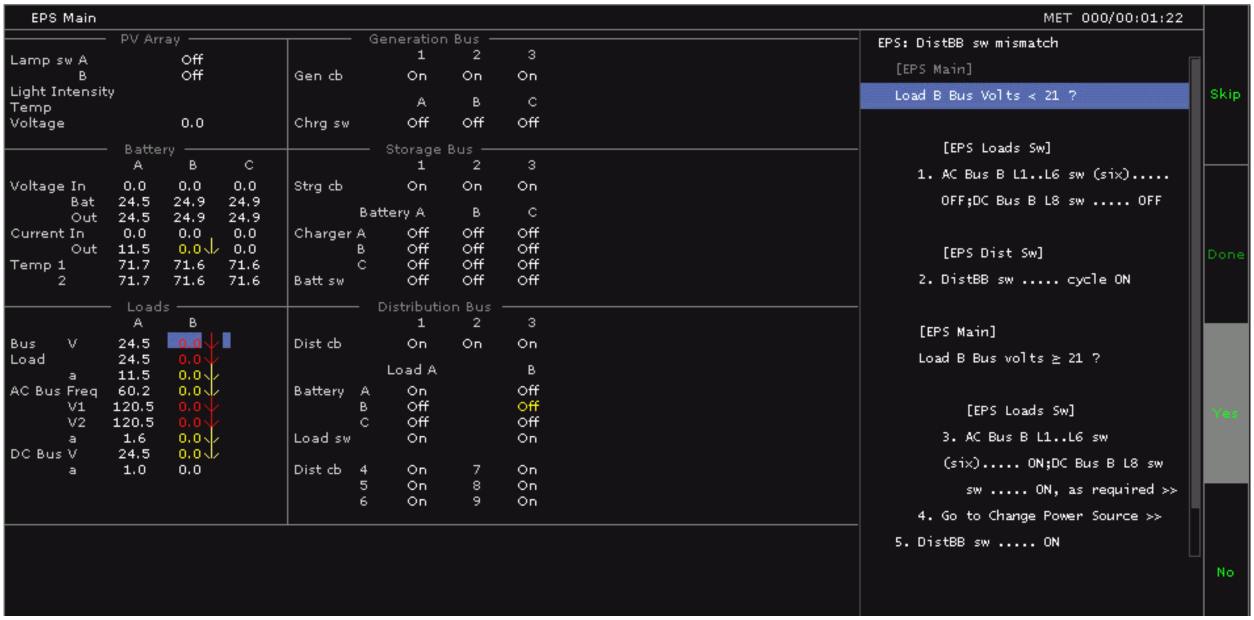


Figure 6-13. Blue Highlight in Elsie Checklist Navigation

schematics/data in the Main Area. In Figure 6-13, the Load B Bus volts value is highlighted in the *EPS Main*. Answering *Yes* to this question will display "Y" in front of the question and bring the focus bar to the first line in the subordinate (left indented) block, *[EPS Loads sw]*. (Answering *No* would have skipped over all the subordinate blocks, and moved your focus bar to the line, "*5. DistBB sw ..... ON*"). Selecting *Do It* will automatically bring up the EPS Loads sw panel in the Main Area (Figure 6-12).

Now, the instruction directs you to set the *AC Bus B L1 .. L6 sw (six);DC Bus B L8 sw ..... OFF*.

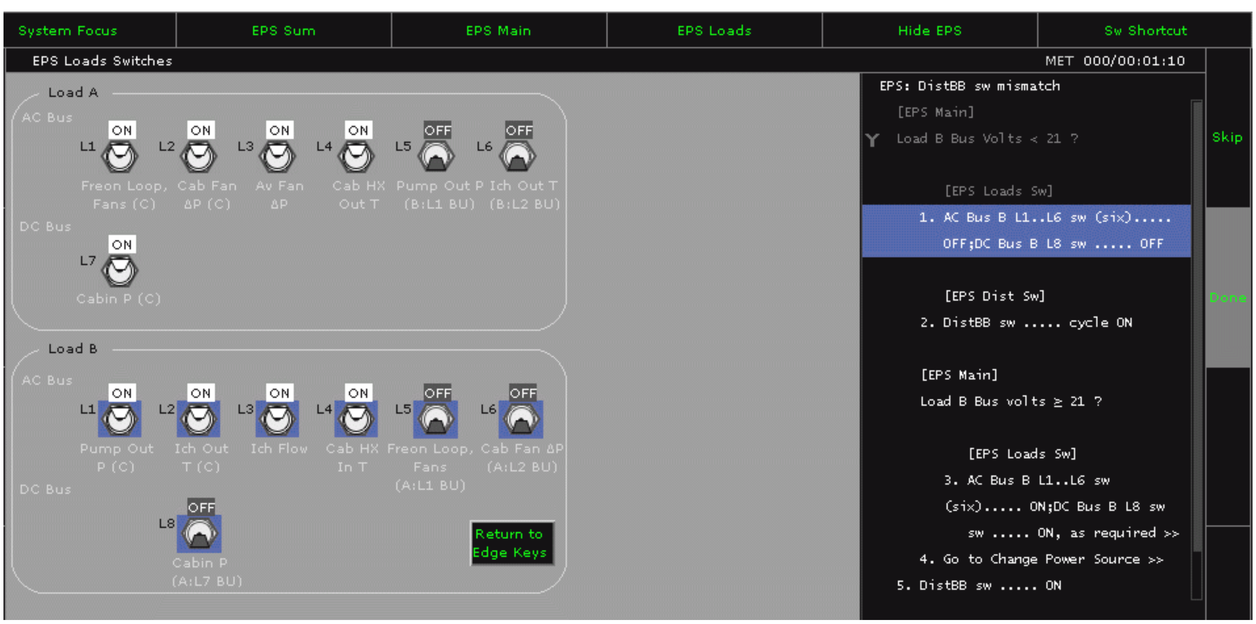


Figure 6-12. Switch Commands in Elsie Checklist Navigation

The corresponding switch icons are highlighted blue in the switch panel (Figure 6-12). If any of them were ON, you need to navigate to that panel and turn them off. A shortcut to the panel, *Sw Shortcut*, is located in the upper-right corner. Upon selecting the *Sw Shortcut* edge key, control of the hand controller transfers inside the switch panel. A green square indicates your current focus on the panel. To change the state of the switch where your current focus is on, hit the Select button on the hand controller. The Select button toggles the state of a switch (turns on a switch if it is off, or turns it off if it is on). When done with all required actions (all blue highlighted components are in the state specified by the procedure instruction), navigate to and select the *Return to Edge Keys* button. This returns hand controller focus to the edge keys. Then, navigate to the *Done* edge key to inform the computer of the completion of that instruction. The blue focus bar then moves to the next instruction and the appropriate components (switches) are highlighted. Continue this process until the *end checklist* line is reached. At that point, the procedure is complete and can be closed or ignored.

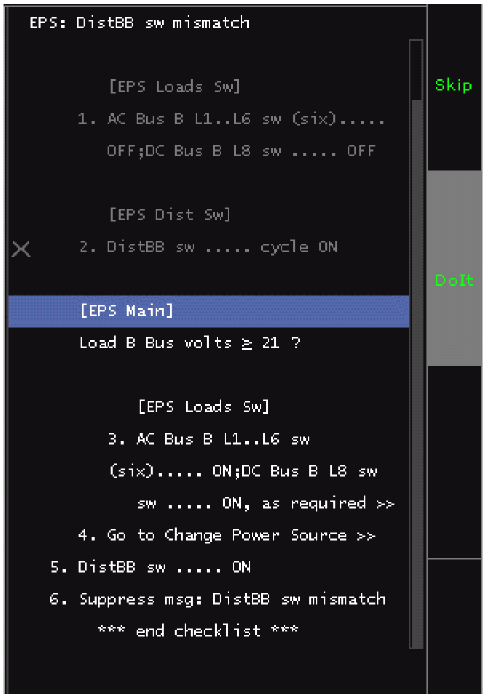
Table 6-1 lists symbols used in the checklist instructions.

Table 6-1. Checklist Symbols

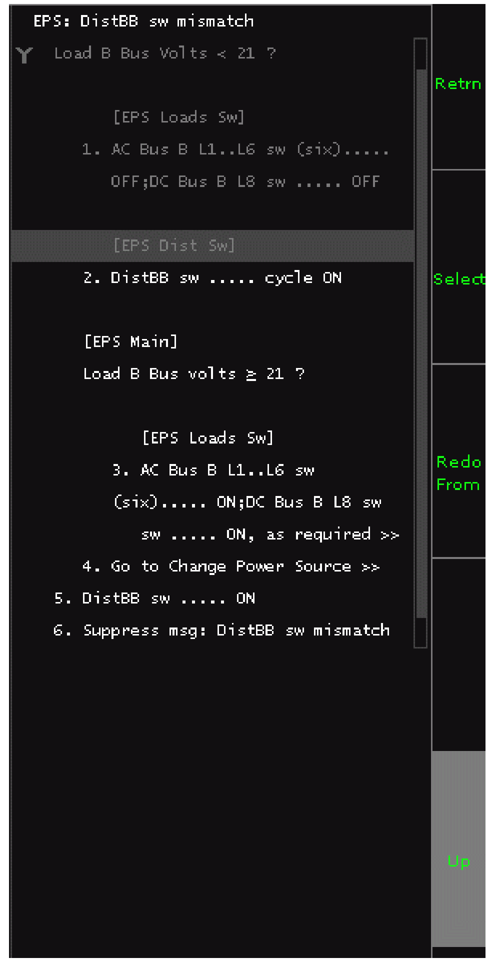
Symbol	Meaning
>>	Exit the procedure.
√	Verify if the statement is true. If not, make it true, or proceed to a different procedure.
[display]	Bring up the display.
*** end checklist ***	End of checklist.

The *Skip* edge key enables you to skip an instruction, if you have a reason to do so. Figure 6-14 (a) shows an example, where "*2. DistBB sw … cycle ON*" was skipped by selecting the *Skip* edge key. The skipped line is marked with *X* and turned to gray color.

What if you accidentally pushed *Done* before completing the instruction or realized that you answered a question wrong? In that case, you can use *Up* edge key to scroll up to the point where you would like to redo from. Once you start scrolling away from the current instruction (either scrolling up or down), the blue focus bar turns dark gray and new edge keys appear on the right as shown in Figure 6-14 (b). Then, select *Redo From* to turn all the lines scrolled over white so that you can redo these lines. The *Redo From* edge key appears only when you scrolled upward. If you scrolled downward, *Skip To* edge key appears in stead of *Redo From*. Selecting the *Skip To* edge key will skip all the lines scrolled over and mark them with *X* (skipped). *Retrn* (Return) edge key will bring you back to the original place that you started to scroll from. *Select* edge key will make only the single instruction current.



(a) Skipping a Line

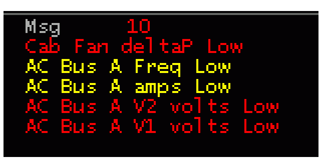


(b) Scrolling Up a Line

Figure 6-14. Checklist Navigation Edge Keys

6.3 Self-Check Quiz

1. To see the connection status of the load switches, go to (EPS Sum / EPS Main / EPS Loads).
2. To see graphical representation of the EPS connections, go to (EPS Sum / EPS Main / EPS Loads).
3. To see textual information of the EPS parameters, go to (EPS Sum / EPS Main / EPS Loads).
4. To turn on/off AC Bus A L2 sw, go to (EPS Dist Sw / EPS Loads Sw) panel.
5. To turn on/off LoadA sw, go to (EPS Dist Sw / EPS Loads Sw) panel.
6. If a symbol of open switch is shown in gray, the switch is open as commanded, i.e., it is not a fault. (true / false)
7.  This icon indicates that the cb is (on (in) / off (tripped)).
8. 

This icon indicates that the commanded position of this sw is (on / off) and the actual position is (on / off).
9. "Switch Failed Open" means that the switch is stuck at (on / off) position.
10. 

When you get C&W messages like this, what is the total number of the messages?
11. (See the figure of #10.) At least one C&W message in the queue is warning. (true / false)
12. Acknowledged C&W messages are erased from the system, and cannot be viewed anywhere any longer. (true / false)
13. White C&W messages in the Elsie Fault Log mean these failures are resolved. (true / false)
14. When you want to see the procedure for "AC Bus A L1 sw inconsistent," which checklist should you look up? (ECLSS / EPS)
15. The symbol ">>" means "exit the procedure." (true / false)
16. The symbol "√" means to verify the statement is true. If it is not true, then proceed to alternative procedure. (true / false)
17. The symbol "[Display]" indicates a title of the sub block. (true / false)

7 Elsie Example

In this section, we will walk you through actual example of the Elsie use.

The ascent-phase simulation started. You brought the Fault Sum page up on the display as recommended. The Fault Sum is a useful display to monitor the overall health of the spacecraft system when you are not working on any fault. Also, when any fault occurs, this display tells you in which Orion system the fault occurred. After a while, an alarm sounded, and you saw the *Master Alarm* lit up red, C&W messages showed up, and both the ECLSS and EPS areas showed red and yellow indications (Figure 7-1). Push the red button on the hand controller (or move the focus to *Master Alarm* and select it) to silence the Master alarm sound.

Figure 7-1. Fault Sum – Right After an Alarm

The colored "A" indicators in the EPS area tell you that something had happened on the Load-Bank-A side of the EPS. In the ECLSS area, all critical components powered by the Load Bank A (that is all except the *Water Loop*) turned to red, which is consistent with the possible problem(s) on the load-bank-A side shown in the EPS area. The Message Area below indicates that there are 14 more messages in the queue in addition to the five shown (i.e., there are 19 messages in total). If there are any messages in the queue, you really should to go to the Fault Log page and view all of the C&W messages to assess the situation. However, first, you decide to take a glance at the EPS schematics. You go to and select the *System Focus* edge key, select *EPS* from the list, and then select the *EPS Sum* (Figure 7-2).

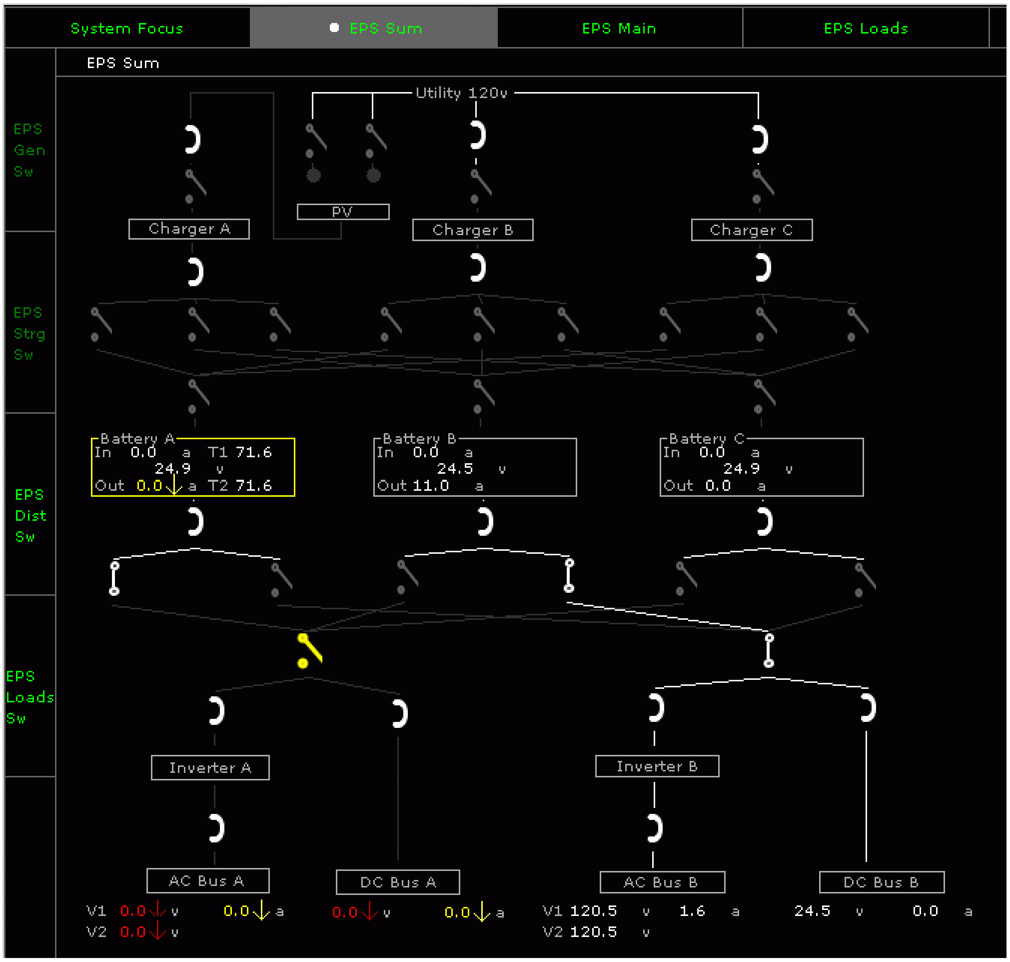


Figure 7-2. EPS Sum

The red and yellow sensor readings at the bottom of the EPS Sum schematics tell you that neither the AC Bus A nor the DC Bus A is getting any electric power. Indeed there is no white line leading in to these buses (compare them with those on the load-bus-B side). A yellow switch symbol in the middle indicates that this switch position is sensed off, inconsistent with the commanded position (on). This explains the lack of current in the downstream components, if the switch is actually off. **Remember, if you see a switch mismatch that is consistent with other sensor readings, it is a very likely candidate of the root cause.** The switch in yellow is called LoadA sw. By the way, the Battery A box is also shown in yellow because the current level of the Battery A Out is low (shown with a downward yellow arrow). However, this low current reading is probably a "child fault" caused by the lack of connected loads in its downstream. Therefore, so far, the most likely candidate of root cause component is the LoadA sw. With that in mind, you go to the Fault Log via the edge key at the bottom of the display (Figure 7-3).

First, whenever you see this many C&W messages on the first page, check if there are any more messages on the page 2 and 3 by selecting the Fault Log edge key multiple times (this will cycle the Fault Log display from the page 1, 2, and 3). In this example, there are 19 messages, and there was one message shown on the page 2.

Figure 7-3. Fault Log

The red messages are warnings related to critical loads, and the yellow messages are cautions related to the non-critical loads. You quickly scanned through them, and found "LoadA sw mismatch" (the 11th message), as you expected from the observation of the EPS schematics. You also found that "Load A Bus volts Low" (at the bottom) was the voltage-low message coming from the most upstream component (i.e., Load Bus). Even though the Load Bus A is more upstream than the LoadA sw, in a case like this where a switch mismatch is present, the switch mismatch is more likely root cause. (If there were no switch mismatch, then look for the most upstream component issuing a voltage-related C&W message. In this case, the Load Bus A volts low.) Therefore, so far, the *LoadA sw mismatch* is the most likely candidate of the root cause.

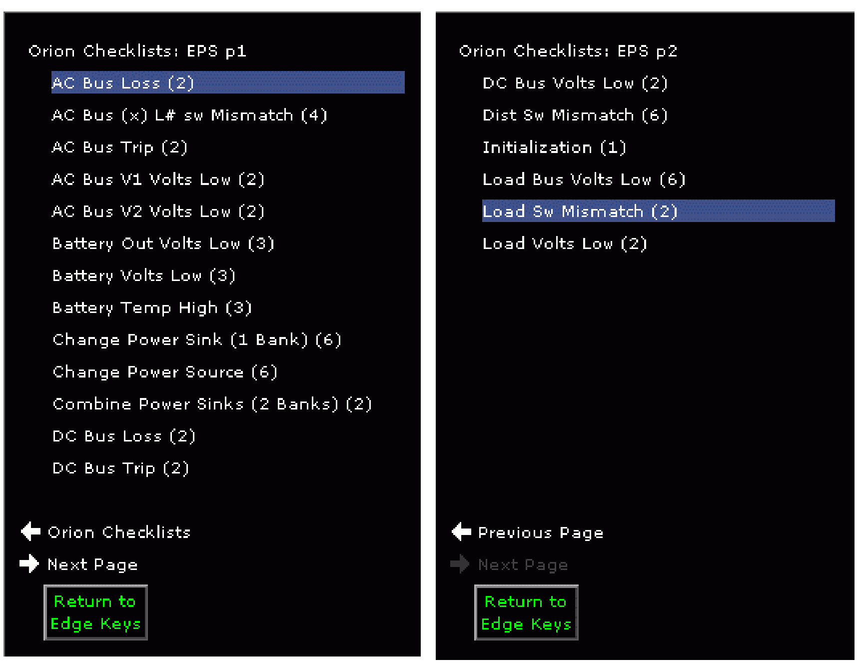


Figure 7-4. EPS Checklist Page 1 (left) and Page 2 (right)

You go to the *Checklist Index* edge key near the lower-right corner to bring up the EPS checklist index (because you already had selected the EPS from the System Focus when you checked the EPS Sum). As Figure 7-4 shows, the EPS checklist contains two pages, and items are listed in the alphabetical order. You found the "Load Sw Mismatch (2)" on the second page. The "(2)" at the end indicates that there are two sub items in this category. Selecting this item brings up a new list containing "LoadA sw mismatch" and "LoadB sw mismatch." You select the "LoadA sw mismatch."

The first instruction of the "LoadA sw mismatch" checklist is a display call-up for the EPS Main (i.e., shown as *[EPS Main]*). Selecting *Do It* edge key will bring up the EPS Main in the Main Area (Figure 7-5). Also notice that the *EPS Main* edge key label shows blue text. During the checklist operations, **blue color is used to guide your attention**.

Figure 7-5. LoadA Sw Mismatch Checklist

The next instruction is a question, "Load A volts < 21?" This question is to check the consistency with the downstream component of the LoadA sw. In the EPS Main display, the corresponding item is highlighted with a blue box. Since the Load A volts (the highlighted item) is showing "0.0," you answer "Yes" via the right-side edge key. This will bring the blue focus bar to the next line, *[EPS Loads sw]*. (By the way, what would have happened if you answered "No?" The checklists are organized using the left indentation. Answering "Yes" brings you to the next left-indented (i.e., subordinate) item located right beneath the question itself. Answering "No" will skip all the subordinate items below the question. In this case, an answer "No" would have brought the focus to the last line, *6. Suppress msg: LoadA sw mismatch*. That basically means that it is probably a false alarm, and thus, you can neglect the C&W message.)

Selecting *Do It* edge key will bring up the EPS Loads switch panel. The next instruction is "1. AC Bus A L1, …, L6 sw (six) ….. OFF; DC Bus A L7 sw ….. OFF." Turning all loads off is a necessary precautionary step in preparing for a switch cycling (turning off then on). If these loads are left on and a switch cycling is attempted in their upstream, high inrush current might damage some of these loads. To get on to the switch panel already opened (in this case, the EPS Loads switch panel), select the *Sw Shortcut* edge key at the upper-right corner. This shortcut edge key provides you a convenient alternative to going all the way to the *EPS Loads Sw* edge key located at the far left side of the display.

When you are on the switch panel, a green square appears indicating your current hand-controller focus. As instructed, turn off all the Load Bus A switches (Figure 7-6). Take time in doing so, because actual physical systems (whose model this simulator is built based upon) may take for a while to turn on/off the current flow. **Do not move the focus away from the switch until you see the talkback (the square label above the switch icon) had responded**. After you turned off all the Load Bus A switches (both AC and DC), go to the *Return to Edge Keys* button to transfer the focus to the edge keys. Select *Done* edge key on the right to proceed.

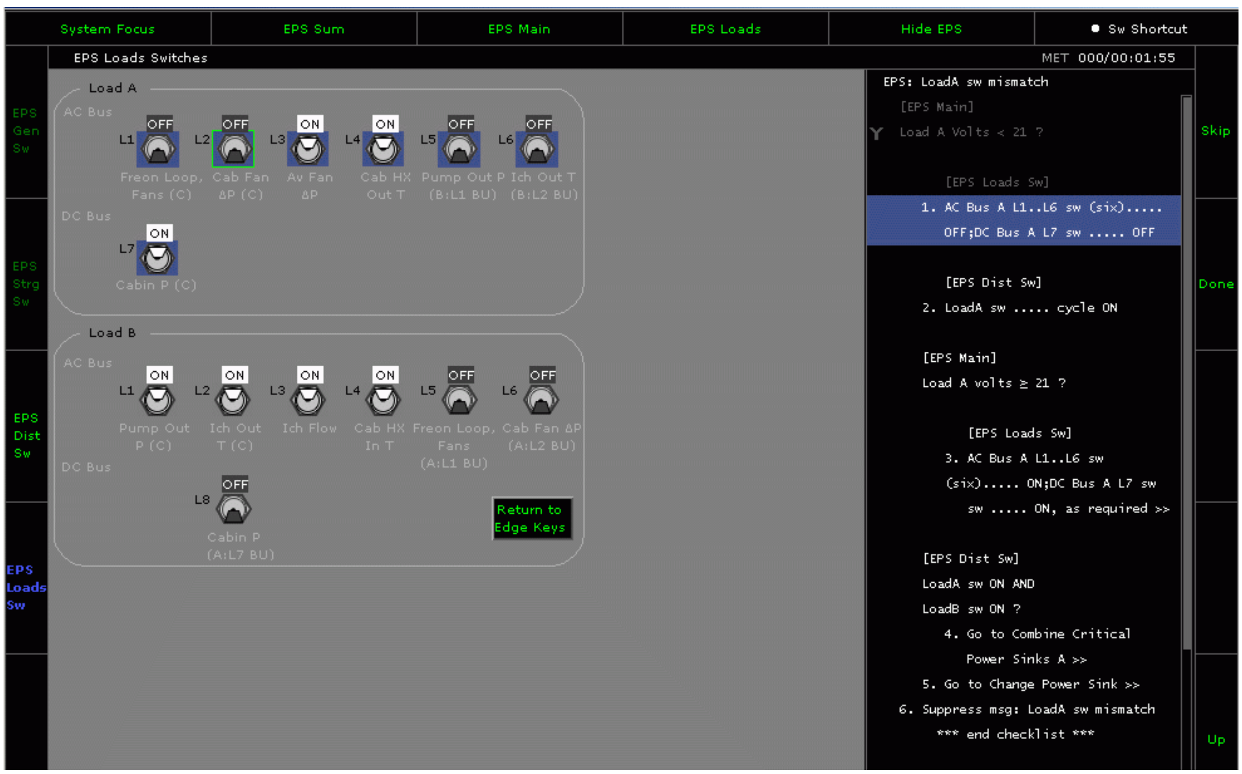


Figure 7-6. EPS Loads Switch Panel

Now, you have turned off all downstream loads, and are ready for a switch cycling. Call up the [EPS Dist Sw] panel – as the checklist instructs – and cycle the LoadA switch (Figure 7-7). Notice that the switch icon is initially on (upward paddle), while the talkback is indicating

"OFF." This was why the C&W message, "LoadA sw mismatch" was annunciated. Cycle the LoadA switch by selecting this icon twice (first one for turning off, then the second one for turning on). Wait one or two seconds to make sure the switch had enough time to respond to your commands. See if the talkback responded to the switch cycling. Actually, in this example, the switch talkback did not respond – not a very good sign…

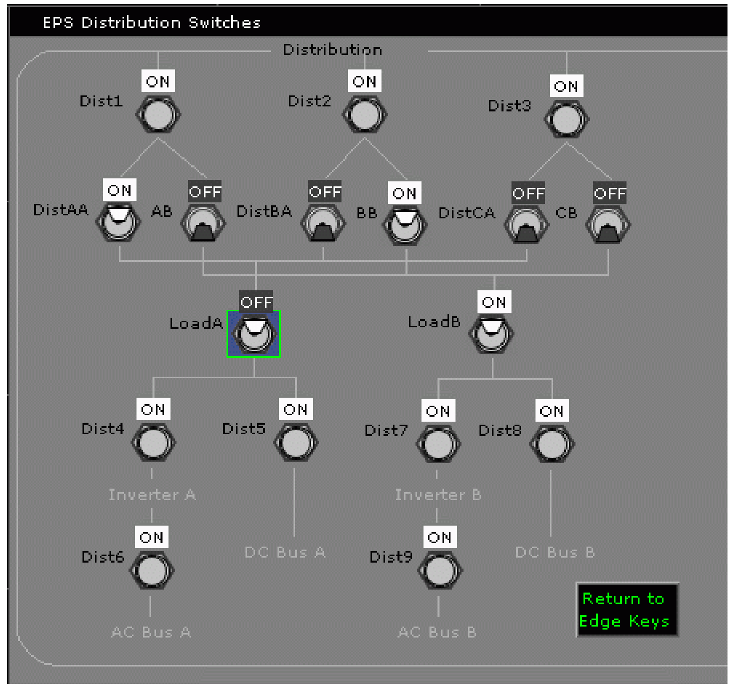


Figure 7-7. EPS Dist Switch Panel

As the checklist instructs, call up the EPS Main, and check the Load A volts value (Figure 7-8). The value is still "0.0." Answer "No" to the question, "Load A volts ≥ 21?" Then, the checklist asks you if "LoadA sw ON AND LoadB sw ON?" This is basically asking you if both the load banks are being used. If so, you will need to move the critical loads on the inoperative load bank (A) to the operating load bank (B). The EPS Dist Sw (Figure 7-7) shows both LoadA and LoadB switches are commanded on, thus the both load banks are being used. Answer "Yes" to this

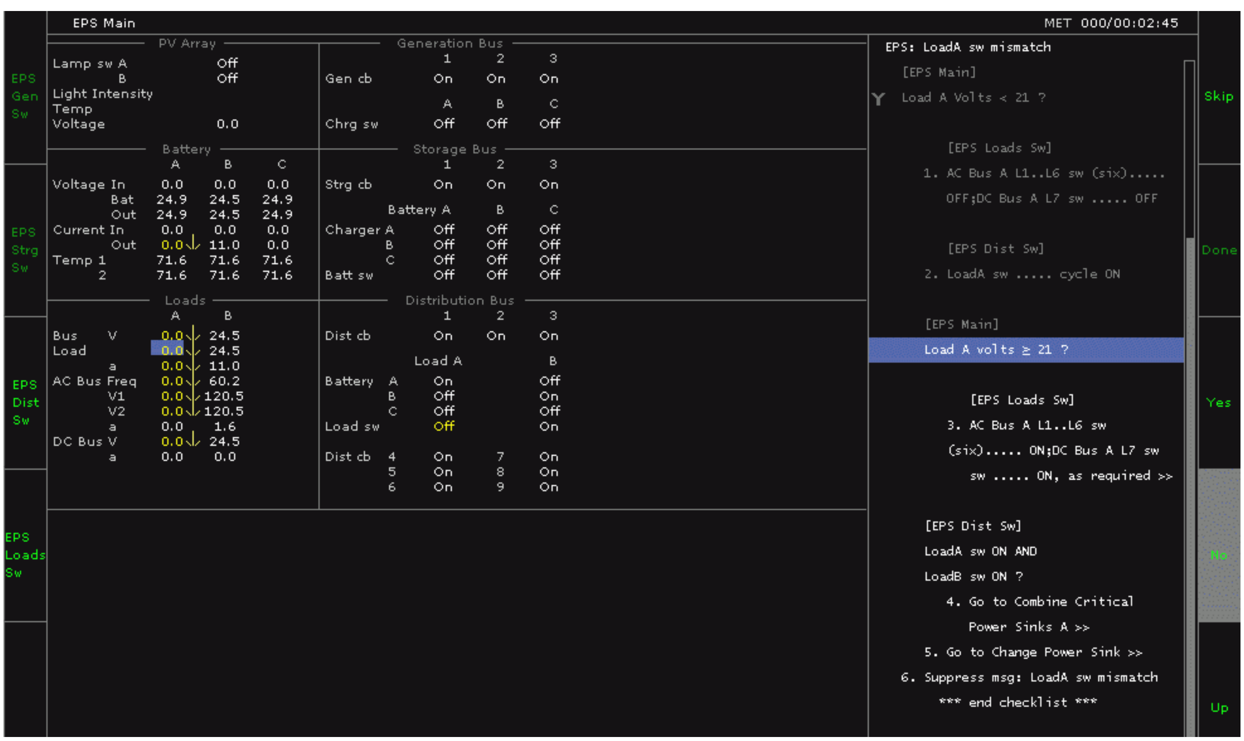


Figure 7-8. Re-Checking Load A Volts after Switch Cycling

question. That means you will need to combine the critical power sinks. The symbol, “>>,” at the end of an instruction means you exit the current procedure.

Go to the *Checklist Index* edge key and select it. In the checklist index, find and select “Combine Power Sinks (2 Banks) (2)” (Figure 7-9). This will bring up a new list that contains “Combine Critical Power Sinks onto Load A” and “Combine Critical Power Sinks onto Load B.” Select the latter, since you are going to combine the critical loads on Load Bank A to Load Bank B.

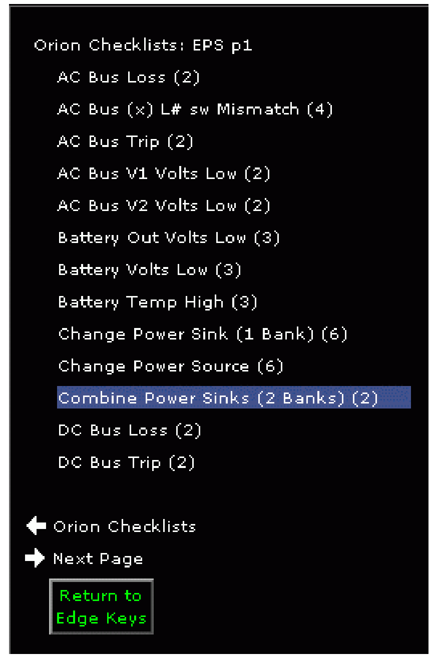


Figure 7-9. EPS Checklist

The first part of the “Combine Critical Power Sinks onto Load B” requires turning off all the loads on the load bank A (Figure 7-10). However, ths was already done due to the previous procedure. So, just select *Done* to proceed. The next instruction is “2. LoadA sw ….. OFF.” Go to the EPS Dist Sw (Figure 7-7), and turn it off (even though it is stuck at off, turn it off any way to completely disconnect the Load A). Select *Done* edge key to proceed.

The next step, “3. √ DistAA, DistBA, DistCA sw (three): OFF,” starts with a symbol, “√.” **The checkmark symbol, “√,” means “verify that this is true.”** If it is true, proceed. If it is not true, then see if you can make it true. If that is not possible, then you may need to perform a different procedure. In this case, the DistAA sw is NOT off, but you can easily turn it off (Figure 7-11). This step ensures that Load Bank A is disconnected from any of the three batteries, prior to moving their critical loads to the load bank B. Turn DistAA off, and select the *Done* edge key to proceed.

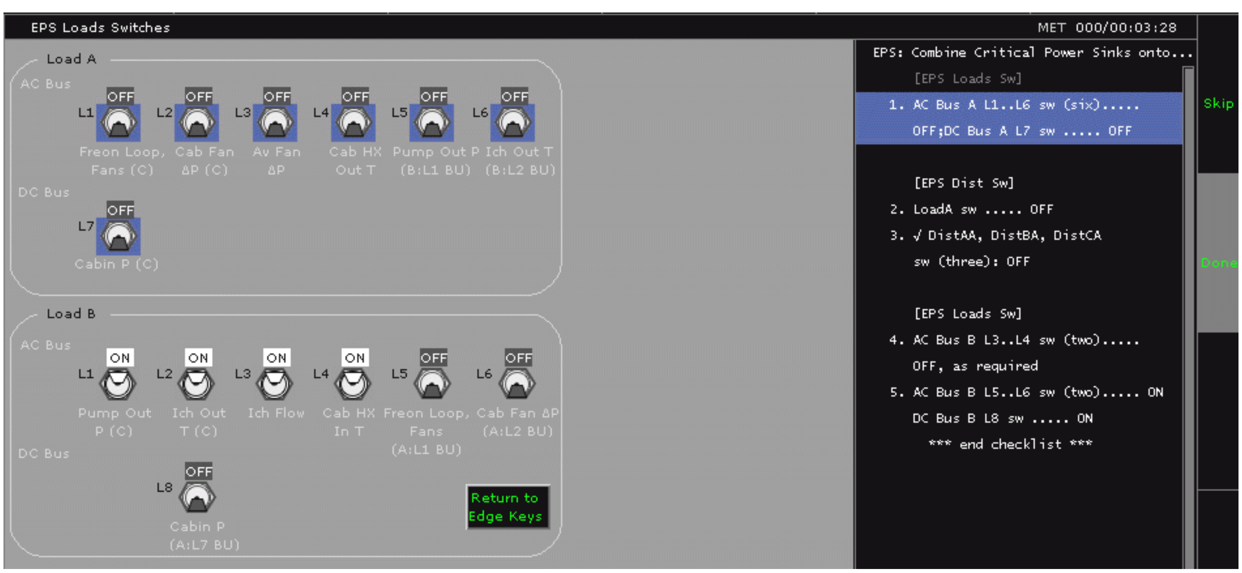


Figure 7-10. EPS Loads Switch Panel for Combining Critical Power Sinks onto B

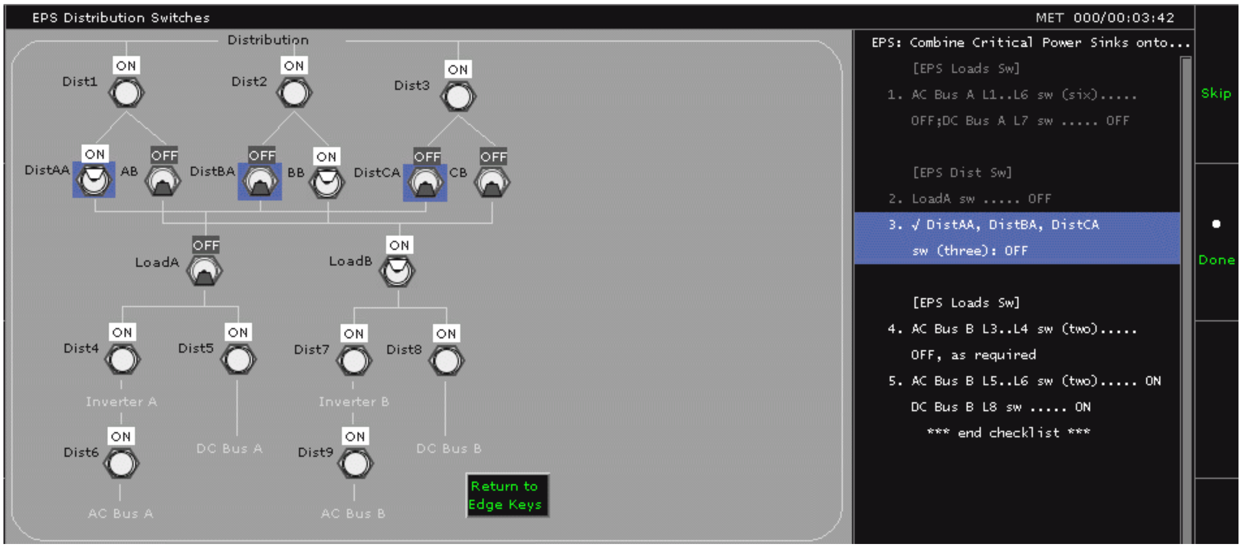


Figure 7-11. EPS Dist Switch Panel for Combining Critical Power Sinks onto B

Now, you are going to turn on the backup of the critical loads. The checklist instructs you that "4. AC Bus B L3..L4 sw (two) ….. OFF, as required." Pay attention to the last part, "as required!" What does this mean? Remember the load-shedding rule? The rule specifies that, when both backup loads (L5 and L6) are to be turned on on Load Bank B, both non-critical loads on Load Bank B (L3 and L4) must be turned off. **The phrase "as required" means "follow the appropriate load-shedding rule."** Note that the load bank A and B have different load-shedding rules. The DC loads do not have any load-shedding rule, because the DC load is a critical load, and you need it to be on (either primary or backup) all the time. Never "shed" a DC load just to make a room for another load.

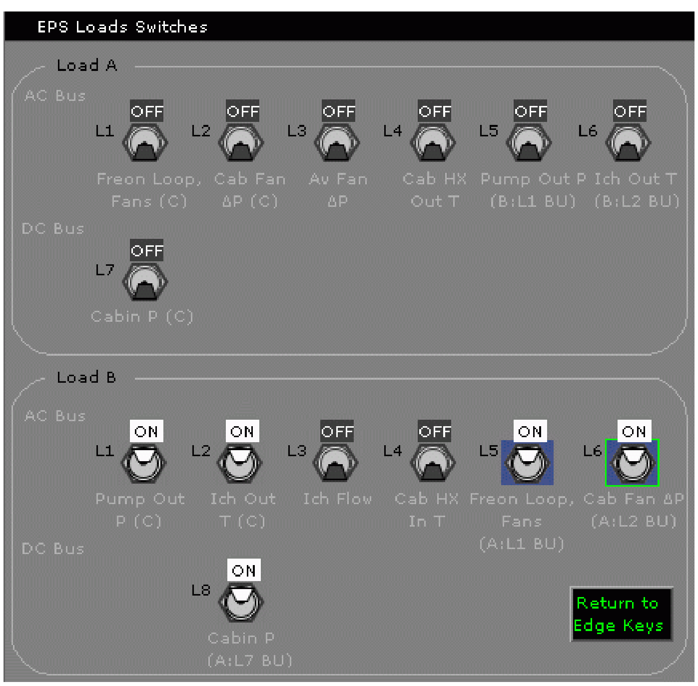


Figure 7-12. Load Shedding

Thus, in this case, turn off the L3 and L4 switches (again, take time to make sure that the talkback responds each time), and then turn on the L5, L6, and L8 (DC load) switches on the load bank B (Figure 7-12). Select the *Done* edge key, and you reach the last line, "*** end checklist ***." That's it. You have completed the procedure, and all the critical loads are now running. To make sure, you can check the EPS Sum, EPS Main, ECLSS, and Fault Sum displays. If everything seems to be OK (i.e., no red), resume your regular monitoring tasks. Bring up the Fault Sum display, if you wish.

8 Besi

8.1 Condensed Approach for Information Presentation

Besi takes the *Condensed* approach, where much of the information presented to the crew is condensed. Besi uses a graphical display for presenting EPS parameters and hides parameters that it determines are not of interest to the crew. The Besi's EPS display also combines parameter monitoring task and system controlling task into one place.

In Besi, each parameter is still monitored by the C&W software. However, rather than relying on predetermined nominal ranges of values, the raw parameter values are sent to a diagnosis software. The diagnosis software feeds these values into an internal model of how the system parameters are interrelated, and determines the "root cause" of the fault. Therefore, unlike in Elsie, the crewmember is provided a single "root cause" message in Besi. All the other details are still available to view at the crewmember's request.

Furthermore, Besi automatically selects the appropriate procedure for a detected root cause and call it up for you. The Besi procedures usually contain much fewer diagnosis steps compared to the Elsie procedures, because the Besi's diagnosis system has an internal system model and already had considered the value of all parameters to make its determination of root cause. However, no system is perfect; so, the crewmember must still verify that the diagnosis is correct by performing minimum amount of diagnosis, where the actual system behavior is compared with the expected behavior. The Besi's *Condensed* procedures walk the crew through this process. If a crewmember determines the diagnosis erred, he then needs to refer to the (hidden, but available) details to determine the correct diagnosis and then proceed to the correct procedure.

8.2 Besi Display Details

1) Start Page

When Besi begins, the crew sees a mostly dark screen (Figure 8-1). There are two selectable edge keys: *System Focus* and *Checklists*. The *Root Cause Select*, *ACK C&W*, *Fault Log*, and *Master Alarm* (top row) edge keys are dim and thus, not initially selectable. The display contains five areas: Schematic/Data Area (upper left), Checklist Area (upper right), System Status Area (lower left), Root Cause Area (lower center), and Fault Message Area (lower right).

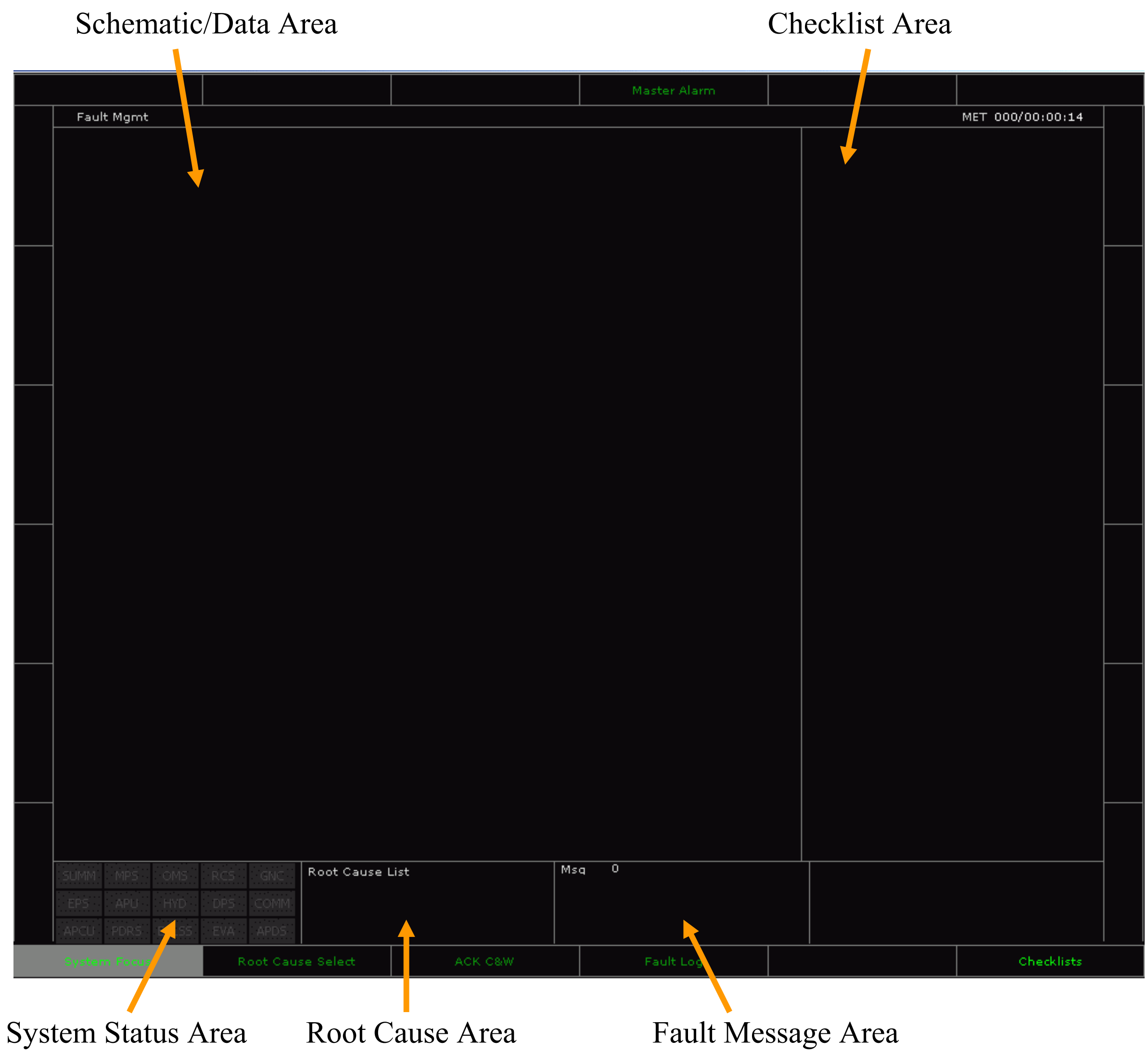


Figure 8-1. Besi Start Page

2) System Status Area

The Systems Status Area contains fifteen annunciator lights to represent the status of each of the fifteen spacecraft systems (Figure 8-2). When all is well within a system, its annunciator light remains dim. If a caution or warning condition is detected, the light will illuminate and three numbers will be printed directly below the system name. The three numbers are colored red,

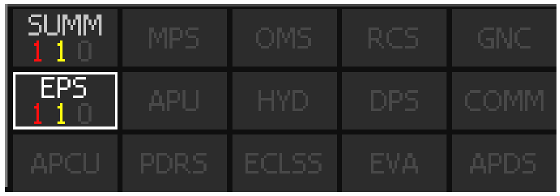


Figure 8-2. Besi System Status Area

yellow and white. The red number is the number of warning-class root causes (related to critical loads) associated with that system, the yellow number is the number of caution-class root causes (related to non-critical or backup loads), and the white number is the number of advisory-class root causes. For example, in Figure 8-2, the EPS contains one warning- and one caution-class root cause. SUMM shows the total numbers of root causes throughout the vehicle.

3) System Focus

To focus on a system, select the *System Focus* edge key at the bottom. This transfers focus of hand controller navigation to the Systems Status Area. Pressing the arrow keys now moves the white rectangle from system to system (again, see Figure 8-2). When on the desired system, press the Select Button. The hand controller focus returns to the edge keys, the selected system is highlighted in the Systems Status Area, and the display associated with that system is brought up in the Schematic/Data Area.

In this experiment, only the ECLSS, EPS, and SUMM rectangles are programmed. The other rectangles will bring up a blank screen. The *SUMM* brings up the Fault Sum display. The *EPS* brings up the EPS display, and the *ECLSS* brings up the ECLSS display.

4) Fault Sum

When the SUMM rectangle was selected in the System Focus, the Fault Sum display shows up in the Schematic/Data Area. This is how the Fault Sum is brought up in Besi. The display is identical with the Fault Sum in Elsie (see ACAWS Displays). As in the Elsie operation, the Fault Sum is a good display to monitor the overall vehicle health when you are not working on any particular malfunction.

5) ECLSS Display

When the *ECLSS* rectangle on the System Status Area was selected, the ECLSS display appears in the Schematic/Data Area. The ECLSS display is shared by Elsie and Besi. Refer the ECLSS section for the display details.

6) EPS Display

When you select the EPS rectangle on the System Status Area, the EPS display appears in the Schematic/Data Area. Besi has different EPS displays from Elsie. Figure 8-3 shows the Besi EPS display. Notice that the title in the schematic area shows that we are looking at EPS (*Fault Mgmt: EPS*) and the systems status area confirms it (EPS and the surrounding rectangle are lit).

The default EPS display in Besi provides graphical representations for voltage, current, and battery temperature for all active (powered) elements. The parameter values are shown using a

Figure 8-3. Besi EPS Display

thermometer type display, but the shapes of the thermometers are altered so that each one resembles the parameter being shown. Thus, a thermometer in the shape of a *V* presents the voltage values, an *A* presents current (or amperes, amps), and a *T* presents temperatures. The fill area corresponds to the nominal area. The highest acceptable values are shown by a red line near the top of the V, A, and T and the lowest acceptable values (if such a limit exists) are shown by a red line near the bottom. For example, when the battery is full, the voltage reaches just to the bottom of the high-limit red line. Similarly, when there is no current being drawn, the A is shown empty (i.e., an unfilled outline). Red symbols indicate that there are warning messages associated with these components (i.e., C&W messages related to critical loads), and yellow symbols mean there are caution messages associated with these components (i.e., C&W messages related to a non-critical loads). The switch and circuit breaker symbols are same as in Elsie's EPS Sum display (refer to Figure 6-3).

Unlike in Elsie, the Loads information is integrated with the EPS schematics in Besi. The little boxes at the bottom of the schematic represent the individual loads. The box color changes to red when there is a warning message associated with the load, or yellow when there is a caution message associated with the load.

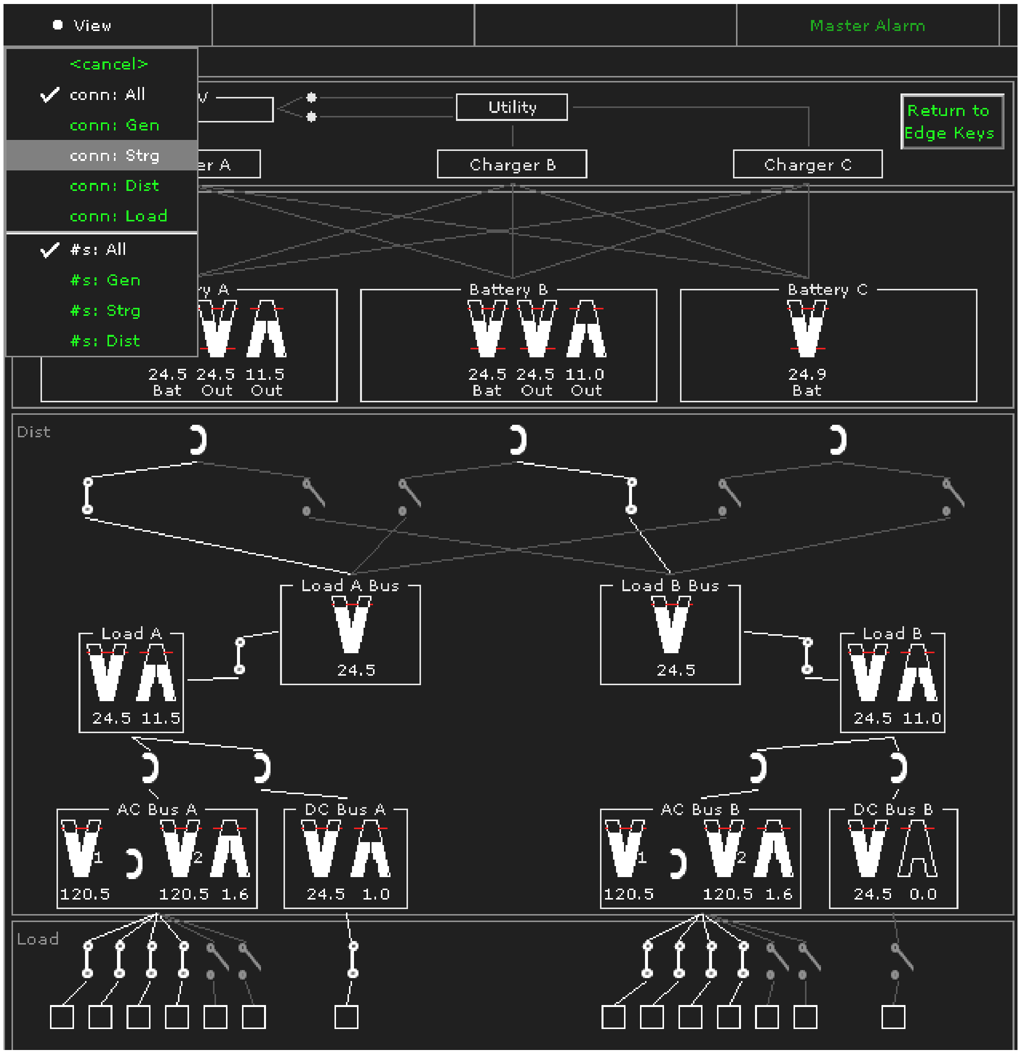


Figure 8-4. *View* Drop-Down Menu

In addition to the EPS schematic, two custom edge keys also appear at the top: *View* and *Connect*. Pressing the *View* edge key near upper-left corner brings up a drop-down menu of options to change the view (Figure 8-4). It enables the crewmember to show connections among components in each of the four sections of the EPS. For instance, *conn: Dist* will show connections in the distribution section. Selecting *conn: All* shows all connections in the four sections at once. In addition, the *View* drop-down menu also enables the crewmember to show digital values for the parameters in each section (e.g., *#s: Dist*) or all three sections at once *(#s: All*). (Since there are no numbers available for the Loads in the EPS schematic, *#s: Loads* is not an option.) Figure 8-4 shows an example after *conn: All* and *#s: All* were selected. Compare it with Figure 8-3 to see the differences.

Selecting the *Connect* edge key near the upper-right corner transforms the schematic display into an active switch-controls display. As soon as the *Connect* is selected, all connections in the four components become visible (just like after selecting *View: Conn: All*), and focus of the hand controller is moved to inside the schematic area (Figure 8-5). Green lines indicate where your current focus is, and can be moved around by the arrow keys on the hand controller. Then, you can toggle the switch status by pushing the Select button on the hand controller (i.e., if it is on, Select button will turn it off; if it is off, Select button will turn it on.)

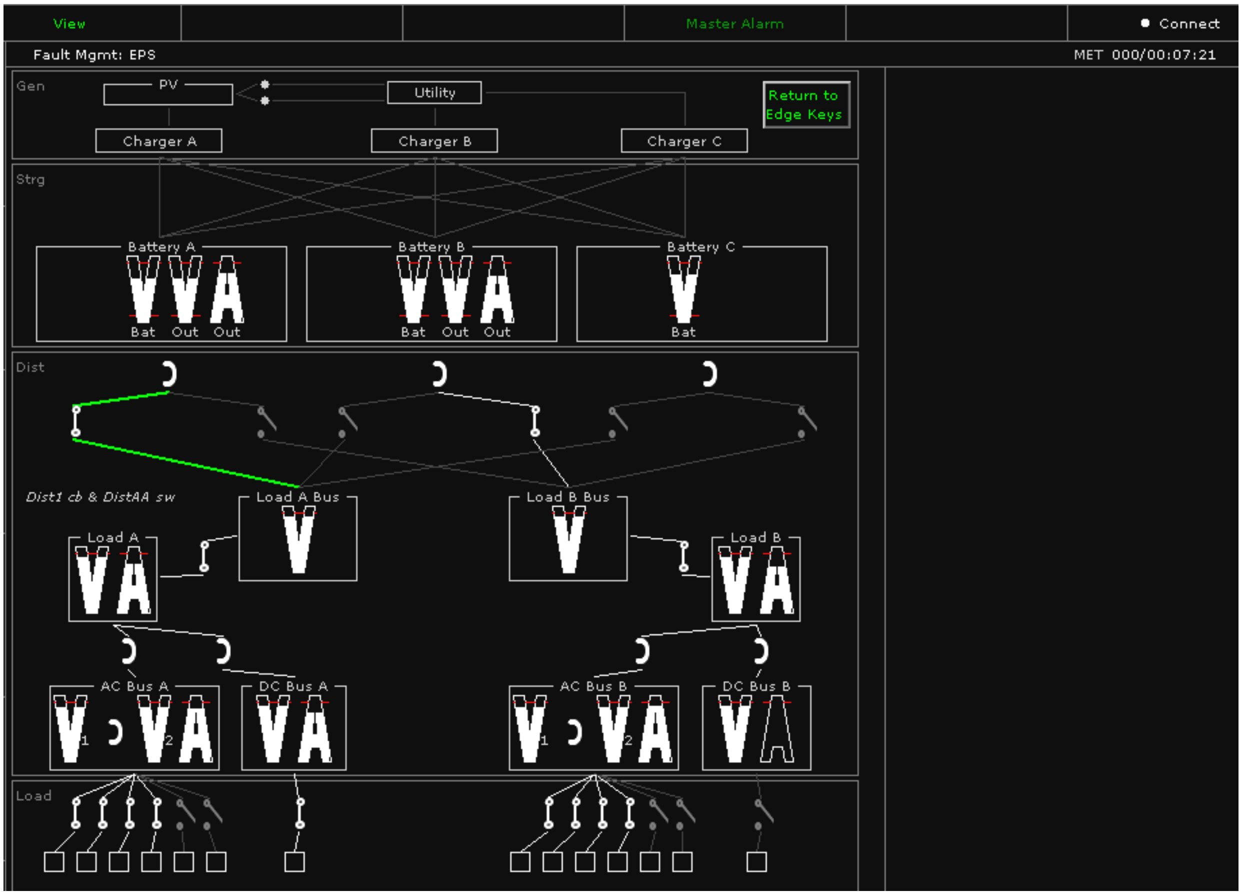


Figure 8-5. Commanding Switches via *Connect*

7) Root Cause Area

One of the major differences between Besi and Elsie is that Besi automatically provides the crewmember root-causes computed by a model-based diagnosis software. The Root Cause Area, an area labeled *Root Cause List*, shows the root cause(s) computed by the software (Figure 8-6). For each fault, the software provides a single, most likely candidate of the root cause. If there are likely multiple separate faults, the diagnosis engine may present multiple root-cause candidates,

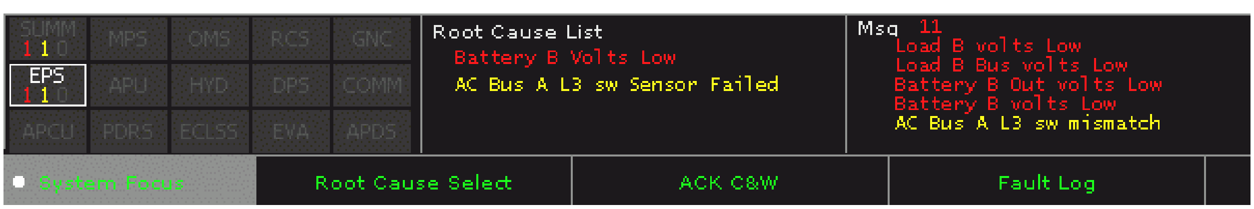


Figure 8-6. Root Cause Candidates and Fault Messages

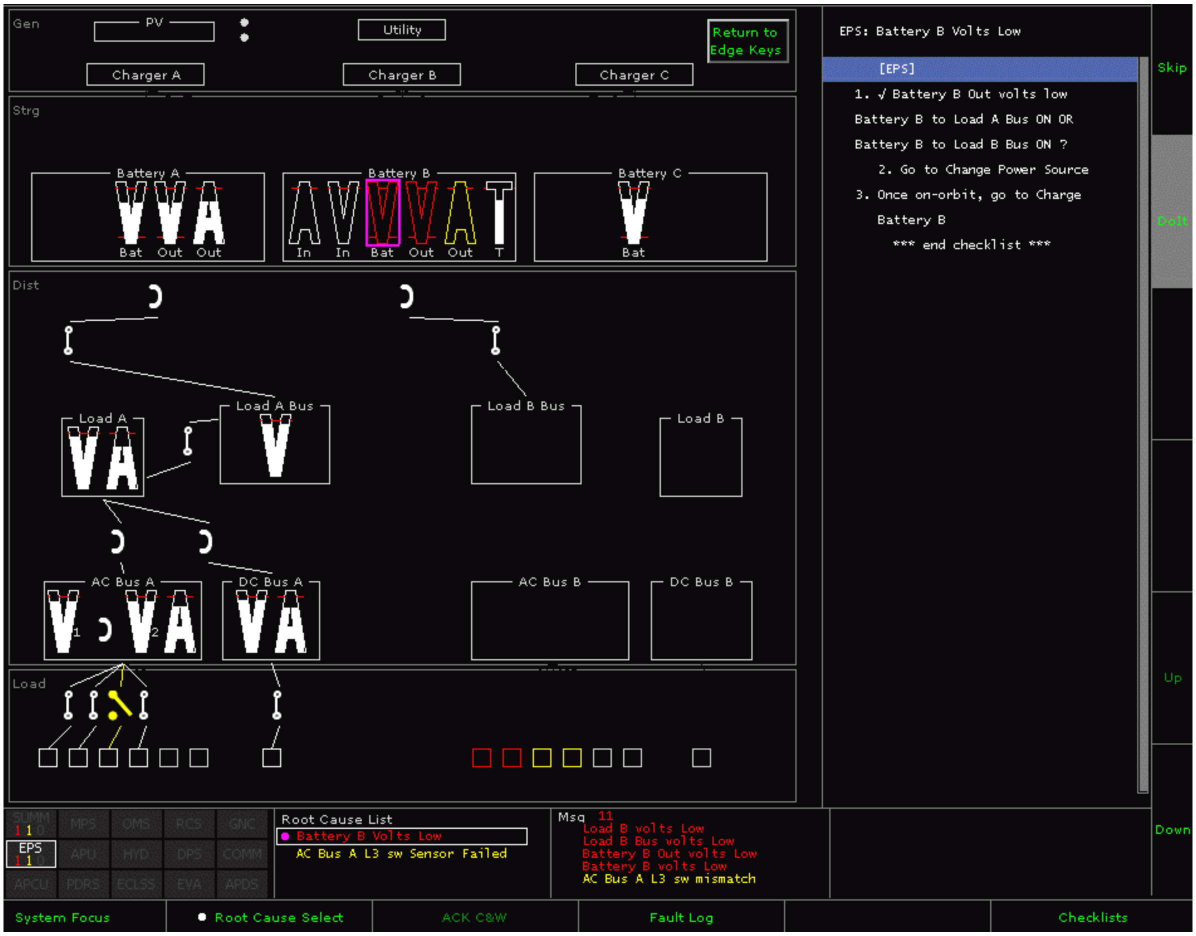


Figure 8-7. Root Cause Select

one for each fault (Figure 8-6 displays two separate root causes). As usual, the root cause texts are color-coded (i.e., red for warning, yellow for caution). The Master Alarm will sound when a new root cause is displayed in the Root Cause Area.

Besi also automatically brings up the checklist corresponding to the root cause. To have Besi bring up the checklist, select the *Root Cause Select* edge key. This moves the hand-controller focus in to the Root Cause Area. A white box indicates the current focus (Figure 8-7). Use the up/down arrow keys to move the focus to the root cause that you want to work on, and then press the Select button. This will bring up the corresponding checklist in the Checklist Area. (In case there is only one root cause in the Root Cause Area, selecting the *Root Cause Select* edge key automatically chooses the root cause and brings up the checklist.) At the same time, a magenta dot appears in front of the root-cause text in the Root Cause Area, and the root-cause component in the diagram is surrounded by a magenta box (see Figure 8-7, where the Battery B volts symbol is surrounded by a magenta box). After you complete the checklist procedures, the magenta dot turns to a checkmark.

8) Fault Message Area

As in Elsie, C&W messages are issued in Besi when any parameter goes out the pre-determined range. These messages appear in the Fault Message Area, labeled *Msg*. (Figure 8-6). As in Elsie, these messages are color-coded (red for warnings, yellow for cautions).

Just like Elsie's Message Area, the Besi's Fault Message Area can hold only up to 5 messages, and the number of the messages in the queue is shown at the top of the Fault Message Area. In the example in Figure 8-6, there are 11 messages in the queue. Thus, there are 16 messages in total, including the five in the Fault Message Area. The color of the number in the queue corresponds to the color of the most severe queued message. That is, if there is a warning message (red) in the queue, the number will be red. If there are only caution messages (yellow), the number will be yellow. As in Elsie, there are two ways to read the C&W messages in the queue: (1) press the *Fault Log* edge key, or (2) press the *ACK C&W* edge key. In the Fault Log display, all C&W messages issued are listed. The *ACK C&W* acknowledges the five visible messages and erases them from the Fault Message area. As a result, the next (up to) five queued messages are pushed forward in the Message Area. The queue number is decremented accordingly. The queue is empty when the queue number is 0. The acknowledged messages turn white on the Fault Log page.

Unlike in Elsie, these messages do not issue the Master Alarm sounds simultaneously. In Besi, the Master Alarm sounds only when a new root cause comes up, which is usually 7 to 8 seconds after the C&W messages are displayed (due to the diagnosis software's computation time).

9) Fault Log

If you want to view the C&W messages in the queue, you can do so in the *Fault Log* (Figure 8-8). The Besi's Fault Log is similar to Elsie's. The major difference is that Besi's Fault Log lists both the root causes and the C&W messages. In Besi's Fault Log, the root cause messages are followed by a left-indented list of associated C&W messages. This Fault Log provides you the details of an automated diagnosis.

When a root cause is resolved (i.e., the corresponding checklist procedure is completed), the dot of the root cause turns to a checkmark. As in Elsie, the messages acknowledged in the Fault Message Area via ACK C&W edge key change to white.

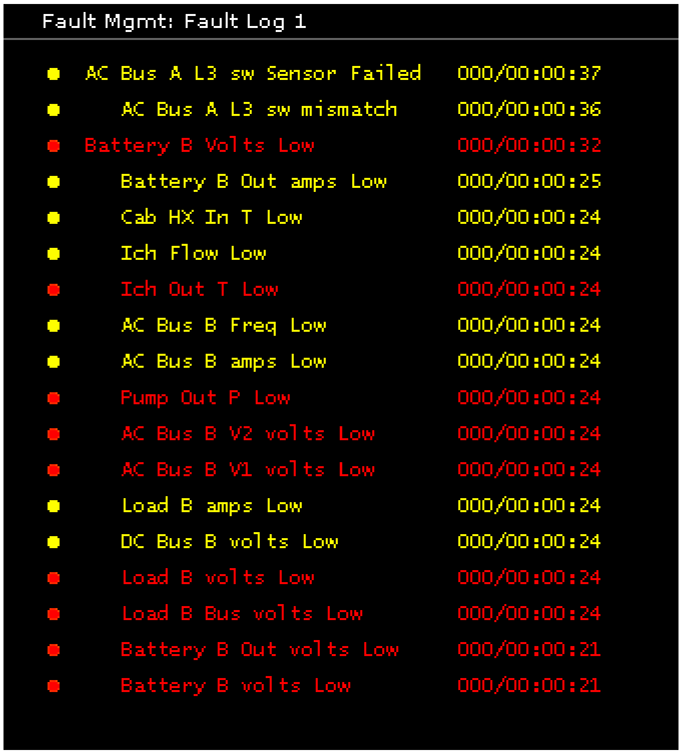


Figure 8-8. Fault Log in Besi

10) Checklist Navigation

The area to the right of the schematic area is where electronic checklists appear. In Besi, a checklist can be brought up automatically by selecting a root cause in the Root Cause Area via *Root Cause Select*. See the 7) Root Cause Area section. The checklist can be also called up manually by selecting the *Checklist* edge key as in Elsie.

Once you get to the checklist, the navigation scheme within the checklist is identical to the Elsie checklist navigation, though the contents of the checklist instructions are different between Elsie and Besi. See the Elsie Checklist Navigation section for more details about the checklist navigation.

8.3 Self-Check Quiz - Besi

1. Selecting SUMM in the System Status Area will bring up ___________ display. (Fault Sum / EPS / ECLSS)
2. Which display is recommended to view when you are not working on any specific problem? (Fault Sum / EPS / ECLSS)
3. In Besi, the Master Alarm edge key lights up red and the alarm sounds when any new C&W message is issued. (true / false)
4. Checklist procedures for the same root cause may be different between Elsie and Besi. (true / false)
5. To view the EPS parameters in Besi, go to EPS Main display. (true / false)

9 Besi Example

Here is a Besi operation example.

The Orion was launched. You brought up the Fault Sum display, the recommended display when you are not working on any fault, by selecting the *System Focus* edge key, and then the *SUMM* rectangle within the System Status Area. Everything seems to be hunky-dory (i.e., all indicators are white). However, suddenly, a slew of C&W messages appeared in the Fault Message Area, and at the same time, some indicators started to turn to red or yellow (Figure 9-1).

Figure 9-1. Fault Sum – Right after an Alarm

The red "A" indicators in the EPS area suggest that something wrong may have happened on the Load-Bank-A side. In the ECLSS area, all ECLSS critical components powered by the Load Bank A (i.e., all except the *Water Loop*) turned to red, which is consistent with the possible problem(s) on the Load-Bank-A side shown in the EPS area. While you are examining the Fault

Sum, the Master Alarm sounded, and the *Master Alarm* edge key on the top lit up in red. You look at the Root Cause Area – a new root cause, "*Load A sw Failed Off,*" computed by the diagnosis software is annunciated (Figure 9-2). You push the red round button on the hand controller to silence the sound and suppress the *Master Alarm* edge key color change.

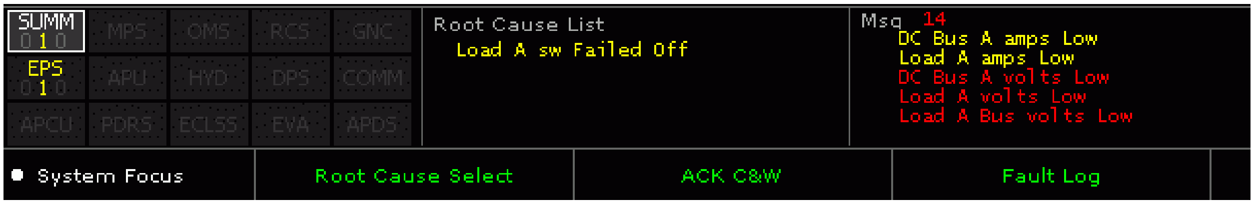


Figure 9-2. Root Cause Diagnosis

Before proceeding to the checklist, you decide to take a quick look at the EPS display first. The EPS display is called up by selecting the *System Focus* edge key, then the *EPS* rectangle in the System Status Area (Figure 9-3).

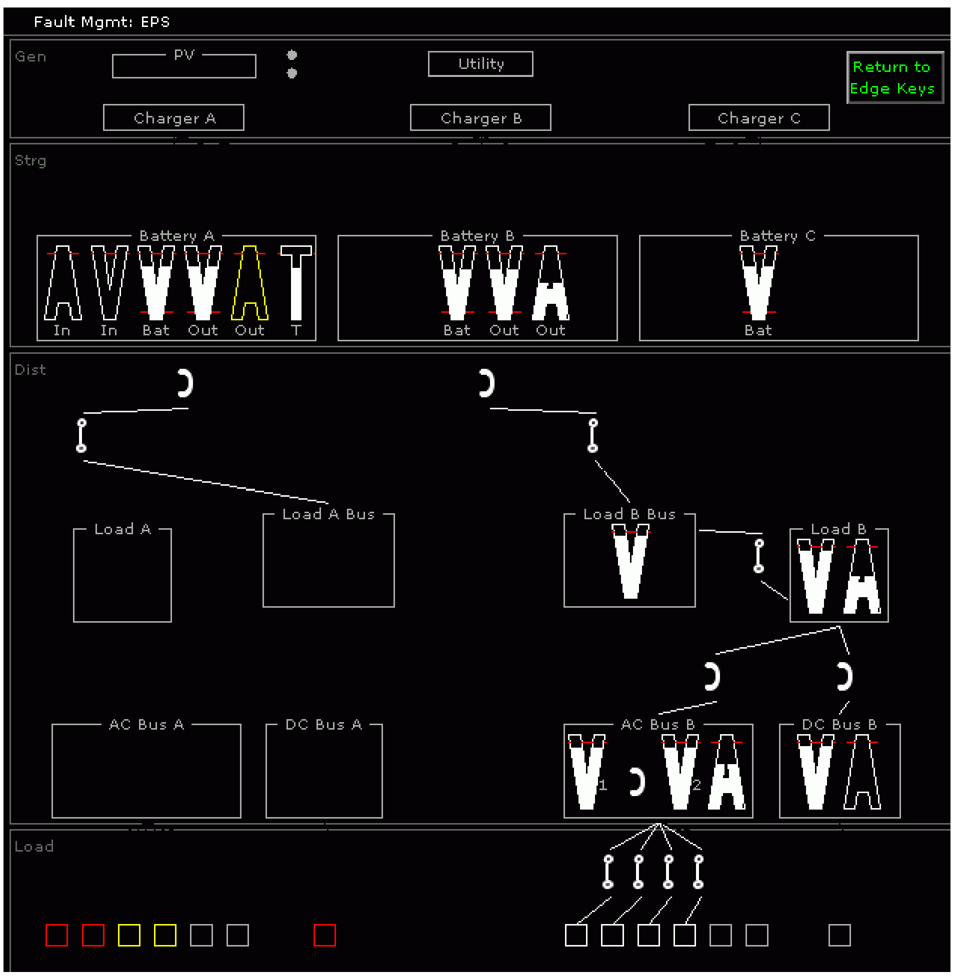


Figure 9-3. EPS Display

The EPS schematics (Figure 9-3) shows empty boxes of the *Load A Bus*, *Load A*, *AC Bus A*, and *DC Bus A*, meaning there is no current on the Load Bank A (compare with the load-bank-B side, which is receiving the current). The lack of white lines in between these boxes also tells you that there is no current flow. The boxes at the bottom represent the individual ECLSS loads, and the red and yellow boxes indicate that their parameters are showing off-nominal values (the critical loads show red boxes, while the non-critical loads show yellow boxes; white are backup). The lack of the current on the load bank A seems to be consistent with the "Load A sw Failed Open" diagnosed by the software (the *Load A sw* is hidden in this view, but located between the *Load A Bus* and the *Load A*).

You can also check the Fault Log display (Figure 9-4). When you see many C&W messages like this in the first Fault Log page, it is always a good idea to check the second and third pages for any additional messages. Selecting the *Fault Log* edge key multiple times cycles the Fault Log pages. In this case, there are two more on the second page.

In the Fault Log, a root cause is followed by the left-indented C&W messages which support the preceding root cause. You quickly glance through the C&W messages, and found "LoadA sw mismatch" (12th line). As mentioned in the Elsie Example section, **whenever you see a "switch mismatch," that is very likely the root cause of the problems in its down stream. (In case there is no "switch mismatch" message, then look for the voltage-low message coming from the most upstream component.)**

So far, all the indications point to the Load A switch failure. So, let's proceed to the checklist.

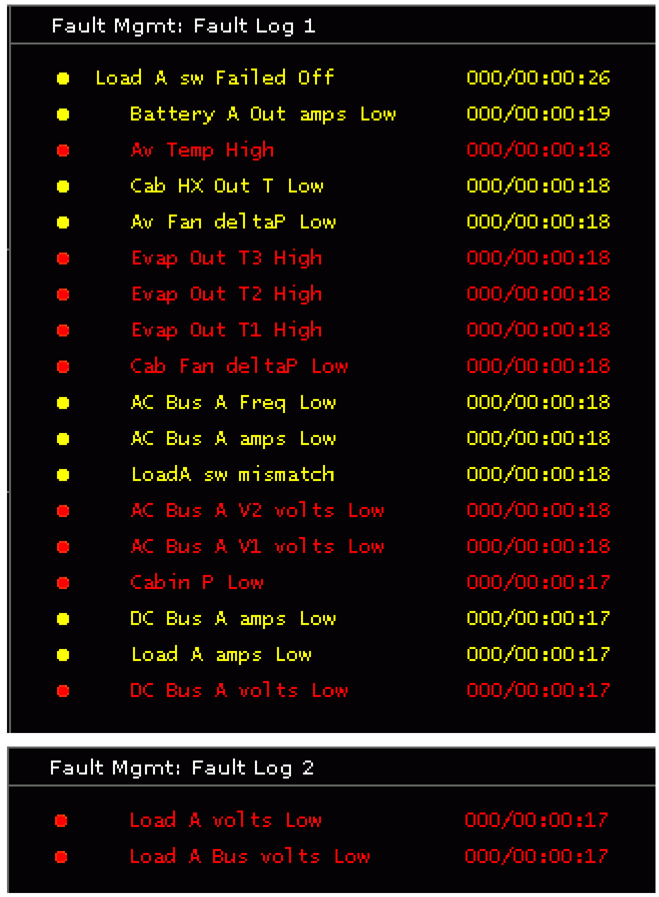


Figure 9-4. Fault Log

Go to the *Root Cause Select* edge key, and select it. Since there is only one root cause in the Root Cause Area, this single action will bring up the *Load A sw Failed Off* checklist in the Checklist Area. The first line is a display call-up for the EPS display. Select *Do It* edge key to automatically bring up the EPS display. Figure 9-5 shows a screenshot after the *Do It* edge key.

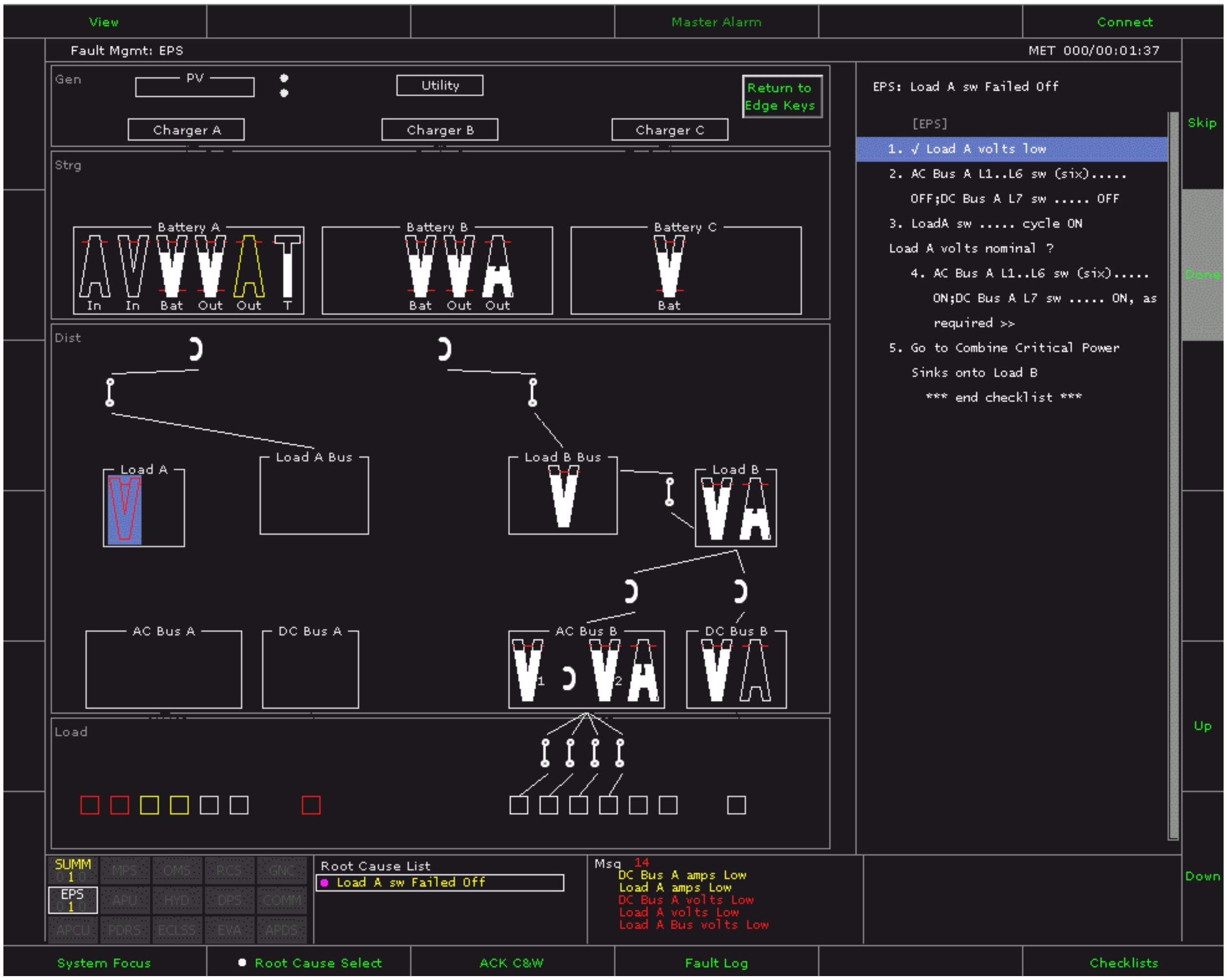


Figure 9-5. Besi Checklist: Load A sw Failed Off

The instruction in the first step has a "√" (checkmark) symbol at the beginning. **The checkmark symbol, "√,"means "verify this is true."** If it is true, proceed. If it is not true, then see if you can make it true, or you may need to perform a different procedure. In this example, the first step instruction is "√ Load A volts low." The corresponding part in the schematics is highlighted with blue to quickly attract the crewmember's attention. The highlighted voltage meter is empty, thus the statement is true. Select the *Done* edge key to go to the next step.

The second step is to turn off all the ECLSS load switches on the Load Bus A (Figure 9-6). This is a precautionary step typically performed prior to cycling a switch in the upstream. This will protect the loads from possible high inrush current when they receive power supply. To turn off these load switches, first go to and select the *Connect* edge key near the upper-right corner. This will move the hand-controller focus in to the schematics. The switches that are instructed to be turned off are highlighted in blue. The green lines are your current focus. Move the green lines to the load switches highlighted in blue and turn them off one by one. Remember that some switches may take a while to respond to your switch throw command due to the dynamic characteristics of the modeled physical components. **Do not move the focus away from a**

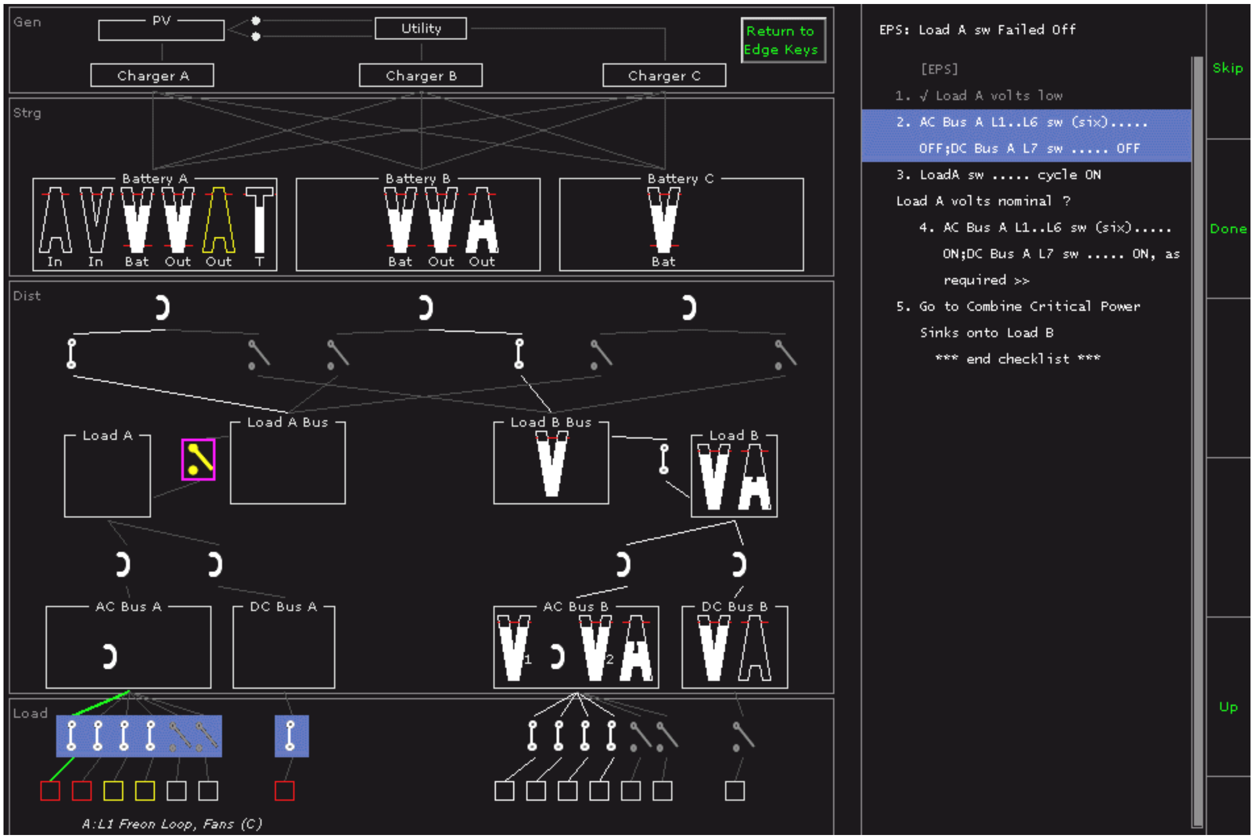


Figure 9-6. Commanding Load Switches

switch before the switch responds to your command (otherwise, you may get an additional switch-mismatch C&W messages).

The third step instructs you to cycle the Load A switch. The symbol of the Load A switch in the schematics is highlighted in blue. Go to and select the Connect edge key to transfer the focus in to the schematics, and then move the green lines to this highlighted switch. Push the Select button twice – one for opening, and one for closing. Select *Return to Edge Keys* to move the focus back to the edge keys. Select *Done* edge key to proceed.

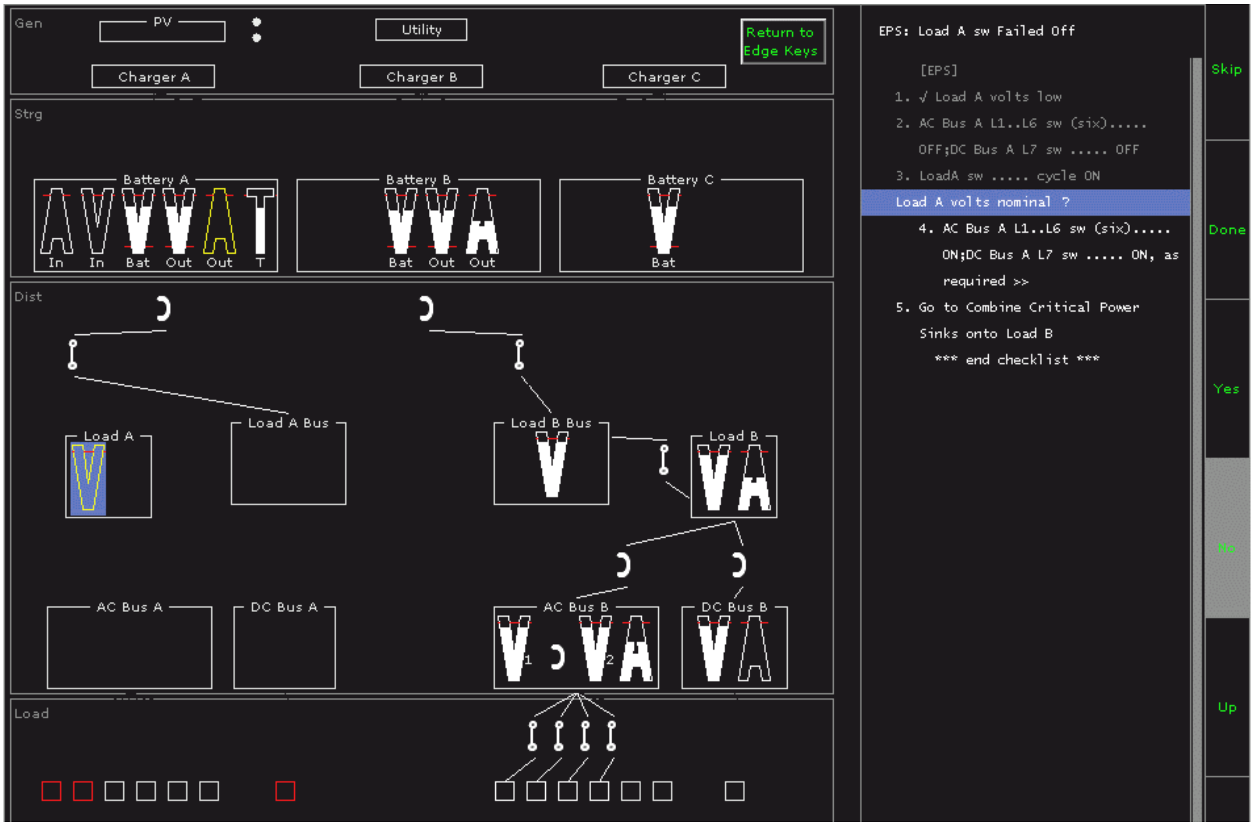


Figure 9-7. After Cycling the Load A Switch

Now, the procedure asks "Load A volts nominal ?" (see Figure 9-7) Actually, the EPS schematics show no sign of current flow on the Load Bank A even after cycling the Load A switch. The voltage meter highlighted in blue (*Load A volts*) is empty. Thus, answer "No" to this question. This will put an *N* in front of the question, and automatically bring the blue focus bar to the fifth step (Figure 9-8). The fifth step instructs to jump to another procedure called *Combine Critical Power Sinks onto Load B*. In Besi, selecting the *Do It* edge key will automatically bring up the corresponding checklist.

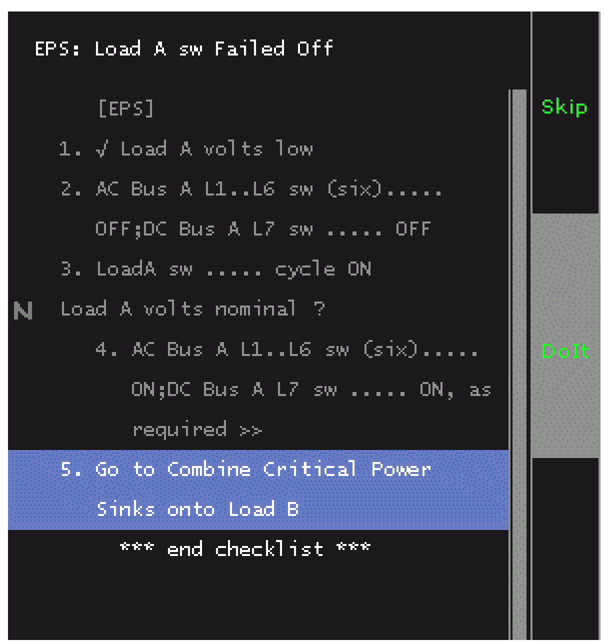


Figure 9-8. Jump to Another Checklist Procedure

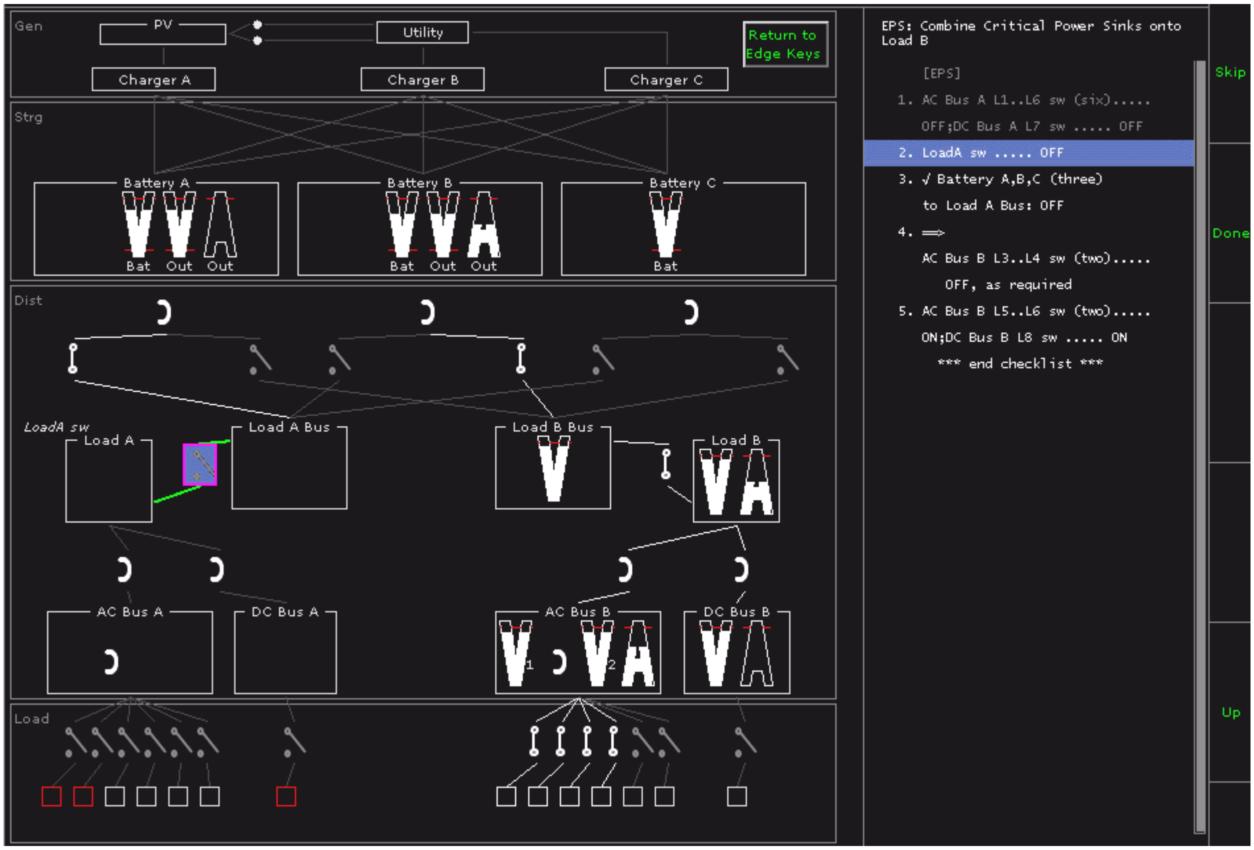


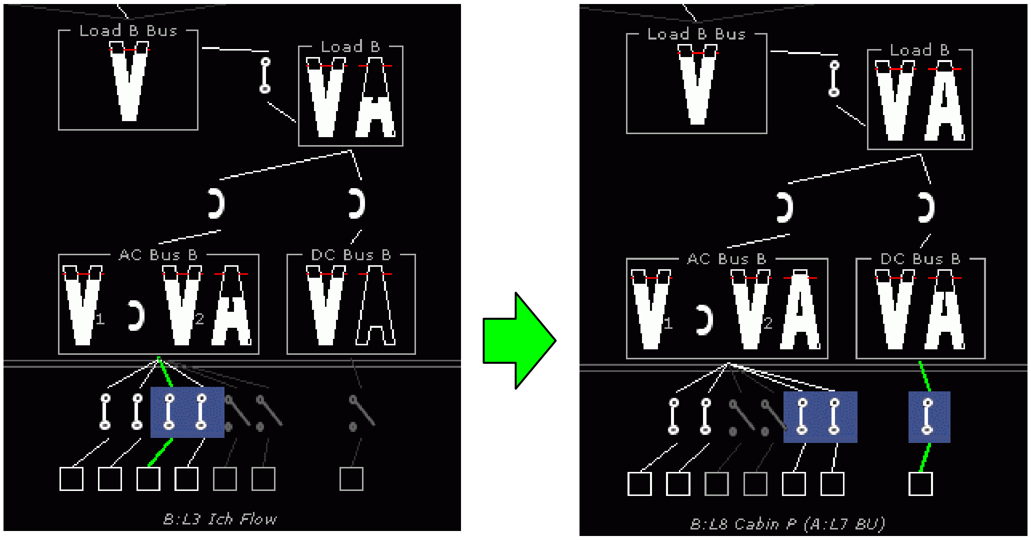
Figure 9-9. Turning Off Load A Switch

The first step of the *Combine Critical Power Sinks onto Load B* procedure is to turn off all the Load-Bank-A loads. Because of the previous checklist, these are already off. Thus, simply select the *Done* edge key to proceed.

The second step instructs to turn off the Load A sw (Figure 9-9). Although this switch is stuck at the open (off) position, turn it off any way to ensure that the load bank A is disconnected.

The third step instructs to turn off all the switches that connect any battery to the load bank A. This is, again, to disconnect the load bank A. This instruction is a "√" (verify) statement. The statement is not currently true because the DistAA switch is on (the DistAA is the switch connecting *Battery A* and *Load A Bus*). Turn the DistAA switch off, and select *Done* edge key to proceed.

You can ignore the "⇒" symbol in the step four (the arrow symbol is for some procedures that jump directly to the step four of this procedure; however, you can safely neglect this symbol because such type of jump will never occur in this experiment). The fourth step, *AC Bus B L3..L4 sw (two) ..... OFF, as required*, is to perform required load shedding on the Load Bank B to prepare for combining the critical load.. Pay special attention to the *as required* part, because the number of the non-critical loads you are shedding depends on the number of the critical loads you are combining. Please read the Load Shedding section in the EPS section (in volume 1) for the specific rules for the load shedding. In this case, since you are adding two critical loads on to the load bank B (L5 & L6), you need to shed both L3 & L4 loads (Figure 9-10). After shedding these non-critical loads, then proceed to the fifth step, and combine the critical loads, L5, L6, and L8 on to the load bank B.



Step 4: Shedding L3 and L4 Step 5: Combining L5, L6, and L8

Figure 9-10. Load Shedding and Combining Critical Loads

When you reach "*** end checklist ***" *Retrn* (return) edge key appears on the right side. Selecting the *Retrn* edge key takes you back to the point in the original checklist, *Load A sw Failed Off*, where you left from. When you complete the original checklist by reaching "*** end checklist ***" line, the magenta dot in the Root Cause Area turns to a checkmark indicating that the procedure is complete. You can also check the EPS Sum, EPS Main, ECLSS, or Fault Sum displays to make sure that all the critical loads are running (i.e., no red).

10 Flight Task

10.1 Flight Task Requirement

To make the operation more realistic, in addition to the EPS-ECLSS monitoring and fault management tasks, we ask you to also monitor the vehicle parameters displayed on the Primary Flight Display (PFD). Please note that this flight task is just as important as the EPS-ECLSS tasks. Therefore, we request you to maintain the PFD monitoring as much as you can, no matter how difficult the EPS-ECLSS tasks become.

The PFD task is actually quite simple. Every so often, one of the parameters on the PFD display will change from its normal white color to yellow. When that happens, your task is to, as quickly and as accurately as you can,

1. Touch the location of the colored indicator on the touch-sensitive display (which will remove the color and restore the parameter to white), and
2. Call out the identity of the indicator

If you don't respond to the change to yellow within 5 seconds, the indicator will change to red for an additional 5 seconds. Your goal at all times should be to monitor the PFD for these color changes, and touch the yellow parameter before 5 seconds elapses (i.e., before the parameter color switches to red). If you missed the "yellow period," it is still better late than never. Please complete the action during the period that the indicator is showing red. The indicator will turn back to white after the 5 seconds of showing red, and if you don't complete the touch-and-call-out procedure in that time, you will be scored as having missed the call-out.

In addition to this color-based task, we would like you to monitor the PFD for two nominal activities, and supply two **nominal call outs** that the CEV operators are supposed to do:

1) "Stage 2" – which means the transition from first stage to second stage ascent. You should monitor the Vertical Situation display and, when the first stage thrust indicator disappears, immediately call out this.

2) "Mode 2" – which means the transition from LAS SEP to abort Mode II. You should monitor the Mode Region Indicator on the Horizontal Situation Display section. When the indicator switches from the LAS SEP to "Mode 2", you should call out this.

Please don't forget to incorporate these nominal call-outs into your PFD monitoring schedule.

10.2 PFD Overview

Here is a brief explanation of the PFD. The PFD is located on top of the ACAWS display. As shown in Figure 10-1, the PFD is composed of three sections.

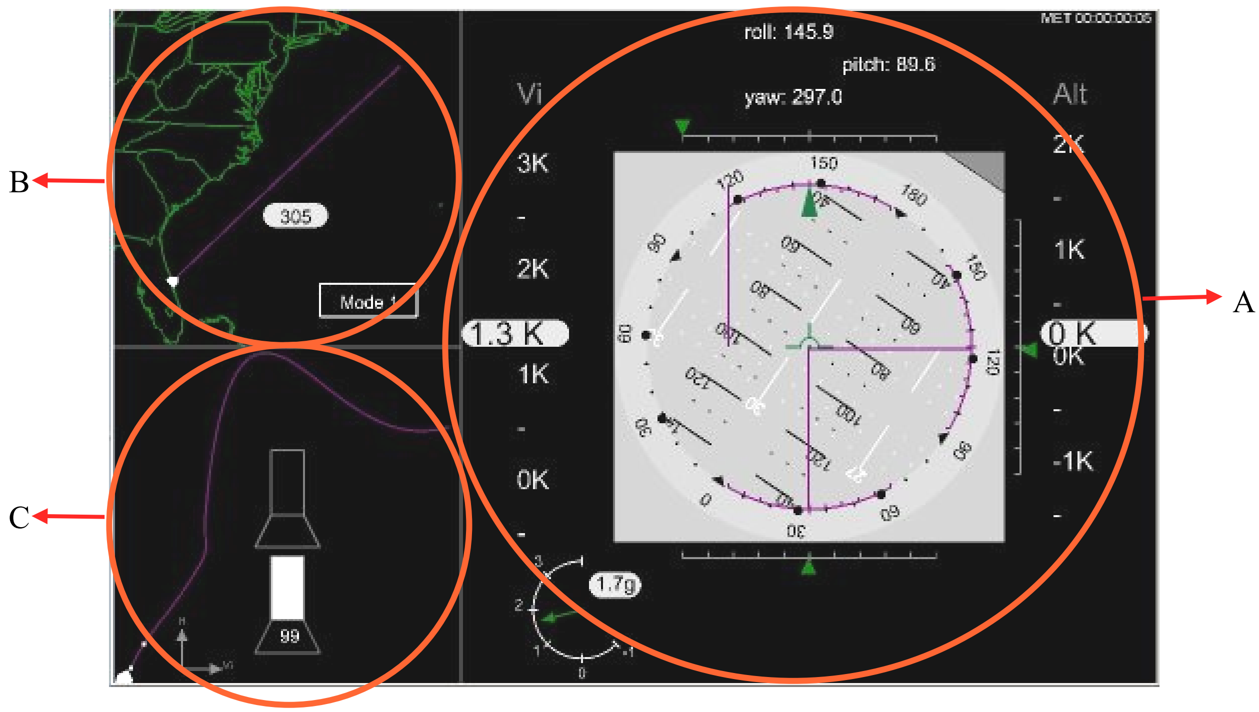


Figure 10-1. Three Main Sections of PFD

On the right (section A) is the Attitude Director Indicator (ADI) which gives you an “inside-out” view of the vehicle’s current pitch, roll and yaw attitude that the crew would use to hand-fly the vehicle if the need arose.

The top left section (section B) contains the Horizontal Situation display (H Sit), which provides the crew a “God’s Eye” view of the vehicle’s current position relative to geographical features on the Earth’s surface. The magenta line shows the vehicle’s trajectory projected onto the Earth’s surface.

The bottom left section (section C) contains the Vertical Situation display (Vert Sit). Here the vehicle’s trajectory is plotted in a Cartesian coordinate system in which the horizontal dimension represents vehicle altitude and the vertical represents inertial velocity.

10.3 PFD Elements You Need To Know

The five PFD elements that change color during the experiment, and thus, you need to be able to call out, are:

1. Velocity
2. Altitude
3. Position
4. G-meter
5. Thrust

Figure 10-2 indicates these five elements (the Position is showing yellow).

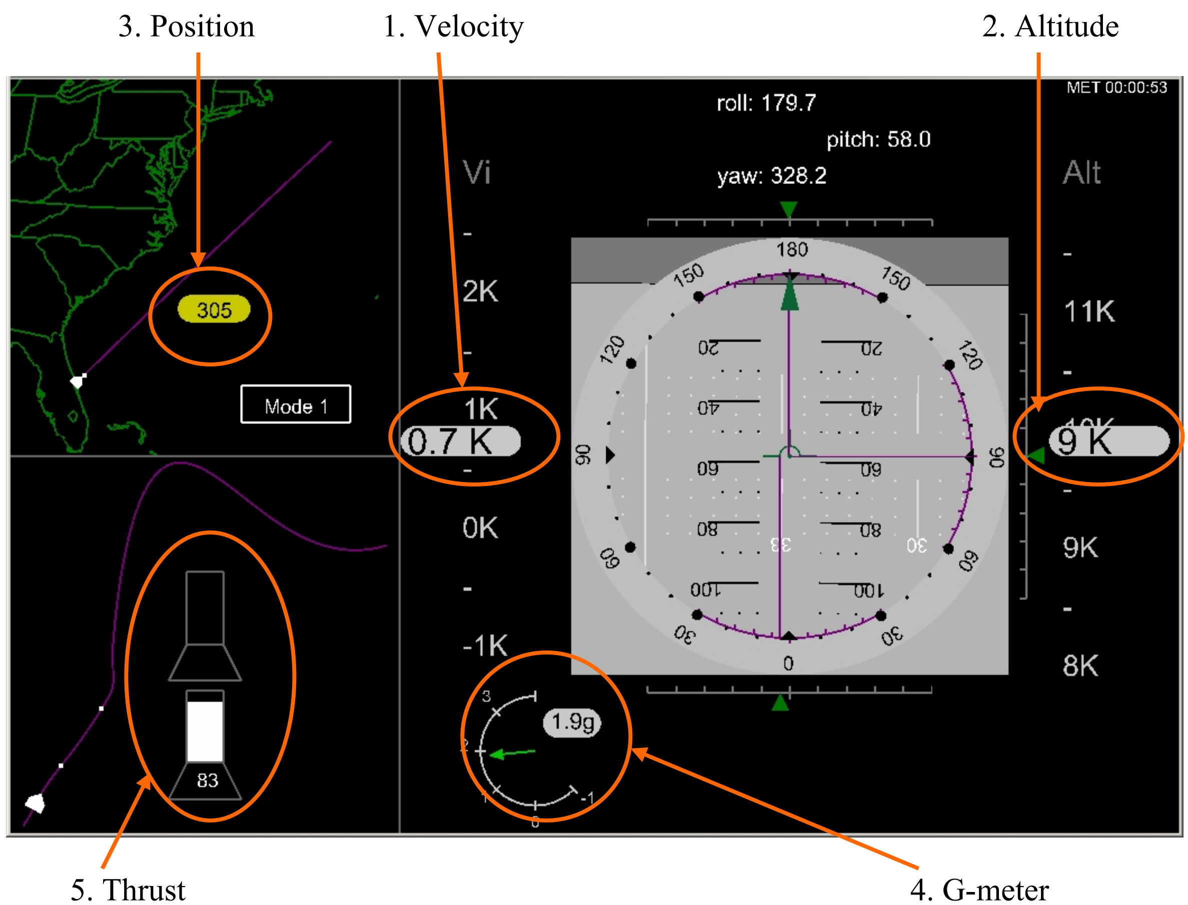


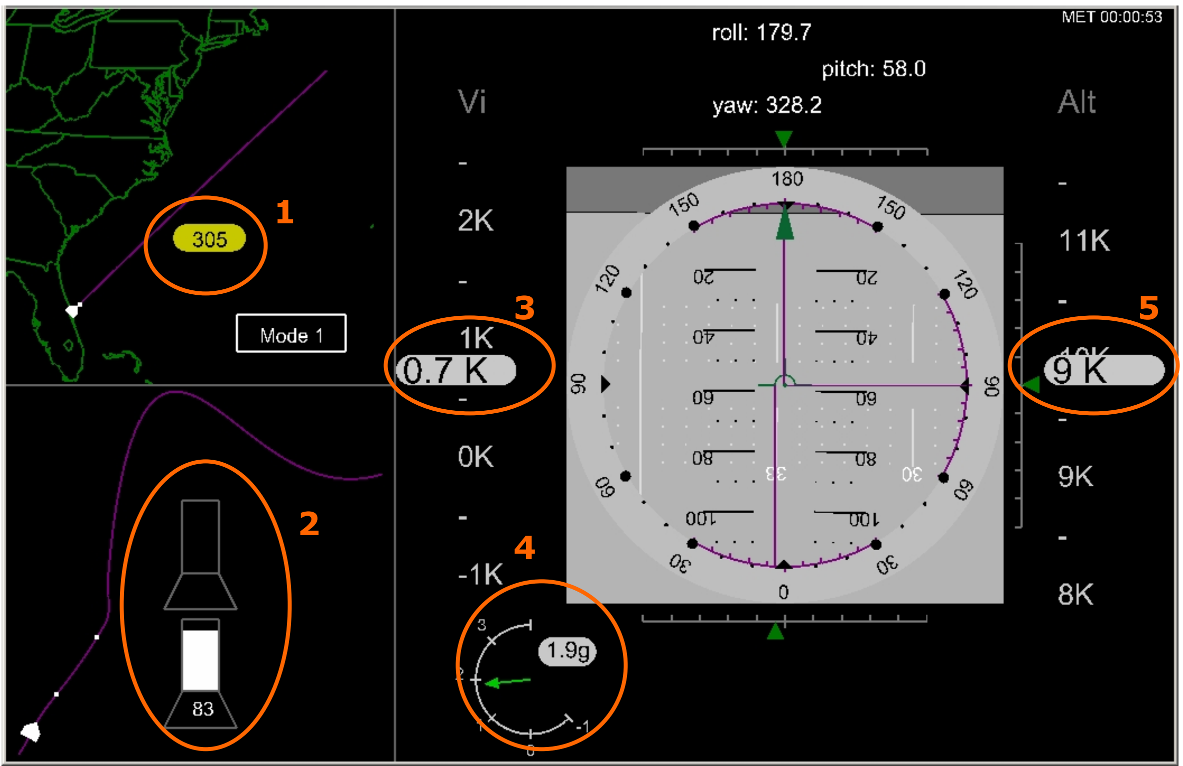
Figure 10-2. PFD Call-Out Elements

For the nominal call outs, the (5) Thrust area indicates the transition from the first to the second stage ("Stage 2" call out), and the Mode Region Indicator (right under the (3) Position, where "Mode 1" is shown in the above example) for the abort mode transition from *Mode 1* to *LAS Separation* to *Mode 2* ("Mode 2" call out).

10.4 Self-Check Quiz – Flight Task

1. (See figure) What are the identities of these 5 PFD parameters?

    1). ____________________
    2). ____________________
    3). ____________________
    4). ____________________
    5). ____________________



2. What are the 2 nominal call-outs?

    1). _____________________
    2). _____________________

Appendix A: Answers to Self-Check Quiz

ACAWS Displays

1. *False*. There are two displays (not three) that are shared by Elsie and Besi, ECLSS and Fault Sum.

2. *Fault Sum*.

3. *True*. A red indication in the ECLSS area in the Fault Sum means that some ECLSS critical load(s) is experiencing malfunction.

4. *True*.

5. *False*. Since all the ECLSS primary critical loads showing off-nominal values (the red *P*s) are powered by the AC Bus A on the Load Bank A, it is very likely that the problem on the AC Bus A is causing all of these ECLSS problems. Therefore, you should go check and fix the EPS problem first (not ECLSS).

Elsie

1. *EPS Loads*. See Figure 6-6.
2. *EPS Sum*. See Figure 6-3.
3. *EPS Main*. See Figure 6-4.
4. *EPS Loads Sw*. See Figure 6-7. The switch for AC Bus A L2 is on the top row, second from the left.
5. *EPS Dist Sw*. See Figure 6-5. The LoadA switch is on the middle row, left side.
6. *True*. Gray switch symbols indicate these switches are open as commanded. Thus, they are not faults. If a switch symbol is shown in yellow or red, that means the switch is either failed open (stuck at off position) or failed close (stuck at on position). This is a switch mismatch, and there is a C&W message associated with it.
7. *On (in)*. The cb icon resembles the physical circuit breakers. If the cb head is shown flat (i.e., no inside circle), the cb is not tripped. See Figure 6-5.
8. *On, off*. The switch icon (paddle) indicates its commanded position, whereas the talkback above indicates the actual position sensed by a switch-position sensor. The distinction may be more obvious when you perform actual switch throws. When you turn on/off a switch, the icon’s paddle reacts immediately, while the talkback above often has delay in the response.
9. *Off*.
10. *15*. The number 10 shown at the top is the number of the messages in the queue. Thus, 10 + 5 = 15.
11. *True*. The color of the number of the messages in the queue reflects the highest criticality of the messages in the queue. In the example, the number 10 is shown in red. That means that there is at least one warning message in the queue.

12. *False*. Acknowledged C&W messages can be still viewed on the Fault Log. The texts of the acknowledged messages are shown in white. See Figure 6-9 for an example.
13. *False*. White C&W messages in the Elsie Fault Log mean that they are either acknowledged (if the dot is yellow or red) or advisory (if the dot is white).
14. *EPS*. The AC Bus A L1 sw is in the EPS, not in the ECLSS. (The EPS Loads Sw panel includes this switch. See Figure 6-7.)
15. *True*.
16. *False*. The symbol "√" means to verify the statement is true. If it is not true, then make it true. If that is not possible, then proceed to alternative procedure.
17. *False*. The symbol "[Display]" means to bring up the specified display.

Besi

1. *Fault Sum*.
2. *Fault Sum*.
3. *False*. In Besi, the Master Alarm edge key lights up and the alarm sounds when any new root cause is presented (not a new C&W message).
4. *True*. Since Besi's automatic root-cause diagnosis software checked the consistencies among the parameters already, the crew needs to go through fewer diagnosis steps in Besi than in Elsie. Thus, the checklist procedures are usually different between Elsie and Besi.
5. *False*. There is no EPS Main in Besi. To view the EPS parameters in Besi, go to the *View* edge key, and select the *#s:* view options. See Figure 8-4.

Flight Task

1. The identities of the 5 PFD parameters are as follows:
   1) Position
   2) Thrust
   3) Velocity
   4) G-meter
   5) Altitude

2. The 2 nominal call-outs are:
   1) Stage 2
   2) Mode 2

Appendix B: Glossary

AC	Alternating Current
ACAWS	Advanced Caution and Warning System
ADI	Attitude Director Indicator (PFD)
Accum Qty	Accumulator Quantity
ACK	Acknowledge
amps	amperage
Av	Avionics Bay
Av Bay	Avionics Bay
BU	Backup
C&W	Caution and Warning
Cab	Cabin
Cabin P	Cabin Pressure
cb	Circuit Breaker
CEV	Crew Exploration Vehicle
CP	Cold Plates
DC	Direct Current
ΔP	Delta P (change in pressure)
dP/dt	Delta P / Delta t (change in pressure)
ECLSS	Environmental Control and Life Support System
EPS	Electrical Power System
Evap Out T	Flash Evaporator Output Temperature
FES	Flash Evaporator System
H Sit	Horizontal Situation Display (PFD)
HX	Heat Exchange
Ich	Interchange
IMU	Inertial Measurement Unit
In	Inlet
Isol Vlv	Isolation Valve
LAS	Launch Abort System
MET	Mission Elapsed Time

Mgmt	Management
msg	Message
N2	Nitrogen (N_2)
NH3	Ammonia (NH_3)
O2	Oxygen (O_2)
Out	Output
P	Primary
P	Pressure
PL	Payload
ppO2	Partial Pressure of Oxygen
PCS	Pressure Control System
PFD	Primary Flight Display
PV	Photovoltaic
Rad	Radiator
SM	Service Module
Sum	Summary
sw	Switch
T	Temperature
tb	Talk back (actual position of the switch or circuit breaker)
Temp	Temperature
Vert Sit	Vertical Situation Display (PFD)